Syntheses and characterization of functionalized cyclodiphosphazane-based frameworks

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2018

Sim, Y. (2018). Syntheses and characterization of functionalized cyclodiphosphazane-based frameworks. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/103669>

<https://doi.org/10.32657/10220/47434>

NANYANG TECHNOLOGICAL UNIVERSITY

DIVISION OF CHEMISTRY AND BIOLOGICAL CHEMISTRY

SCHOOL OF PHYSICAL & MATHEMATICAL SCIENCES

**SYNTHESES AND CHARACTERIZATION OF
FUNCTIONALIZED CYCLODIPHOSPHAZANE-BASED
FRAMEWORKS**

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Acknowledgments

First and foremost, I would like to express my gratitude to my supervisor aka Boss, ***Asst Prof. Felipe García***, for accepting me as his PhD student. I am extremely thankful for his patience in tolerating how unorganized and stubborn I am in all aspects. Not just a PI, he has been guiding and teaching me countless important life skills throughout my 5 years in the lab, better equipping me to face the working society in the future.

Next, I would like to thank all my labmates, past and present - ***Dr. Hu Zhang, Dr. Wang Jingyi, Mr. Ong How Chee, Dr. Davin Tan***. Special mention to ***Dr. Shi Xiaoyan*** who I have worked with on various projects. They are the ones who listen to all my rants and complaints and tolerate my black-face every morning. The mundane lab life has been much enjoying with them around. Thanks for countless laughter and joy over the years. In addition, I am blessed to have the colleagues from other labs for their concerns and small talks occasionally.

To my fellow PhD friends (***Sebastian, Sabrina, Luthfi***) thanks for going through this tedious journey together. Never fails to offer listening ears and bring some sanity back to me when I got mentally and emotionally exhausted. Also, I would like to specially thank my groups of friends who have supported me and not forgetting me despite my constant absence for gatherings. Special mention to ***Liwen*** who gets me out of lab whenever possible for meet up, listening to my random rants, and always showering me with gifts.

I would like to thank the NTU staffs, ***Dr. Rakesh Ganguly, Dr. Li YongXin, Miss Goh Eeling, Mr Derek Ong, Mr Keith Leung*** and ***Miss Joan Pang***, for the assistance provided throughout the years.

Lastly and most importantly, to my family, *Dad, Mum, Sister, Brother in-law, Brother, Sis in-law* and my *niece* and *nephews* - thanks for supporting my decision to embark on this journey. Many treats from Sister whenever we meet up to catch up on our lives and always keeping a lookout for your younger sister here. Special thanks to the kiddos for chasing my blues away with their cuteness and showed me how much one can learn when one set one's mind to it.

This journey has been a long and fruitful one despite the numerous breakdown moments. However, that's what research (and life) is all about, and only after these challenges, it makes you a better chemist and, of course a stronger human.

All in all, thanks for everything and
everyone I have met in this journey!

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Abstract

Cyclodiphosph(III)azanes are four-membered ring compounds, made up of alternating trivalent phosphorus and nitrogen atoms. They are generally highly air and moisture sensitive, therefore hindering their utility in many areas. Their syntheses and manipulations require strict exclusions of oxygen and moisture to minimize the possibility of oxidation and hydrolysis. Moreover, the incompatibility of cyclodiphosph(III)azanes to protic solvents and the poor solubility of organic nucleophiles of interest pose difficulties in synthetic procedures as we work towards expanding the family of functionalized cyclodiphosphazane-based frameworks. Hence, we employed mechanochemical ball milling as a synthetic alternative to generate desired cyclodiphosph(III)azane compounds. On top of that, air- and moisture-stable cyclodiphosph(V)azanes are synthesized in orthogonal one-pot one-step manner (*Chapter 3*). In general, the nucleophilic substitutions of dichlorocyclodiphosph(III)azanes result in formation of new P-N, P-O, P-S or P-C bonds. In this thesis, a new class of P-O(carboxyl) bond is further investigated *via* oxidation reactions (*Chapter 4*). Despite the vast examples of cyclodiphosphazanes known, they typically lack functionality for further reactions. Therefore, it hinders the exploration and development of potential applicability of cyclodiphosphazanes. With these inadequacies identified, ester has been introduced into the targeted cyclodiphosphazane frameworks in view to increase the utility. The isolated compounds were fully characterized and described in *Chapter 5*. Lastly, the syntheses of tris(cyclodiphosphazane) compounds are described along with that of a novel extended P₂N₂-based macrocycle (*Chapter 6*).

Abbreviations

ACN	acetonitrile
Ad	adamantyl
AFM	atomic force microscope
Ar	aryl
C ₆ D ₆	benzene-d ₆
br	broad
ⁿ Bu	normal-butyl, (C ₄ H ₉)
^t Bu	<i>tert</i> -butyl, (CH ₃) ₃ C
δ	chemical shift
Calcd	Calculated
CCDC	Cambridge Crystallographic Data Centre
CDCl ₃	chloroform-d ₃
cm ³	centimetre cube
Cy	cyclohexyl (C ₆ H ₁₁)
d	doublet
DCM	dichloromethane
dd	doublet of doublet
Dipp	2,6-diisopropylphenyl, 2,6- <i>i</i> Pr ₂ C ₆ H ₃
Et	ethyl, C ₂ H ₅
Et ₂ O	diethyl ether
F _w	molecular weight of asymmetric unit (g mol ⁻¹)
FTIR	Fourier Transform Infra-red
hr.	hours
HRMS	High-Resolution Mass Spectroscopy
<i>J</i>	coupling constant (Hz)
K	kelvin
MeOD	methanol-d ₄
m	multiplet
m.p	melting point
[M+1] ⁺	parent ion bound to H ⁺
m/z	mass to charge ratio, unit for mass spectroscopy
Me	methyl, CH ₃
Min.	minutes
Mes	mesityl, 2,4,6-(CH ₃) ₃ C ₆ H ₂
Mes*	2,4,6-tri- <i>tert</i> -butylphenyl, 2,4,6- ^t Bu ₃ Ph

mL	millitre
MS	molecular sieves
NaCl	Sodium chloride
NMR	nuclear magnetic resonance
ρ_{calc}	calculated density (mg cm^{-3})
Ph	phenyl, C_6H_5
ppm	parts per million
<i>i</i> Pr	<i>iso</i> -propyl, $(\text{CH}_3)_2\text{CH}$
Py	pyridyl, (NC_5H_4)
q	quartet
quin	quintet
RBF	round-bottomed flask
s	singlet
t	triplet
T	temperature (K)
<i>m</i> -Ter	2,6-bis(2,4,6-trimethylphenyl)
THF	tetrahydrofuran
TMS	tetramethylsilane, $\text{Si}(\text{CH}_3)_4$
Tol	toluene
μ	linear absorption coefficient (mm^{-1})
ν	wavenumber (cm^{-1})
<i>V</i>	cell volume ($\text{\AA}^3$)
VT	variable temperature
λ	wavelength ($\text{\AA}$)
wR2	R-factor (weighted)
Z	number of formula units per unit cell

Chapter 1 - Introduction

1.1 - Cyclophosph(III)azanes

Pnictogen(III)-nitrogen ring systems are cyclic compounds, consisting of alternating trivalent pnictogen and nitrogen atoms. Some examples are cyclodiphosphazanes, cyclodistibadiazanes, cyclodibismadiazane, cyclotriarsazanes and cyclotetraphosphazanes.¹⁻⁸

Figure 1.1. Examples of phosph(III)azane-based frameworks ranging from acyclic, fused rings, cyclic, cages to anionic derivatives.⁹⁻¹²

The pnictogen-nitrogen system of interest for this thesis is cyclophosphazane frameworks which belong to part of a bigger group known as the phosphazane family. This family comprises of compounds ranging from acyclic frameworks (type **I – V**), rings (type **VI – X**), chains (type **XI**), fused rings (type **XII**), cages (type **XIII – XIV**), macrocyclic arrangements (type **XV – XVII**) to anionic derivatives (type **XVIII**) (Fig. 1.1).⁹⁻¹² Among these phosphazanes presented, there are several types of the compounds (type **XI – XII**, **XIV – XVIII**) which were obtained from cyclodiphosphazane of type

VI – VIII. With the ease of synthetic manipulations and vast possibilities for the type **VI – VIII** cyclodiphosphazanes, they were further identified as the primary research interest for our research group and thus, the focus of this thesis was to investigate the expansion on the different varieties of cyclodiphosphazane-based frameworks.

Figure 1.2. Examples of acyclic disubstituted cyclodiphosph(III)azanes with P-C, P-N and P-O bonds respectively.^{13–18}

Since the focus was narrowed to cyclodiphosphazanes, it is essential to first define the term ‘cyclodiphosphazanes’. Cyclodiphosph(III)azanes are four-membered ring compounds made up of alternating trivalent phosphorus and nitrogen atoms, where the oxidation state of phosphorus atom is denoted within brackets.¹⁹ They are also the smallest unit of cyclic phosphazanes where $n = 2$ in the general formula of $[XP(\mu\text{-NR})]_n$. To date, there has been a large volume of such cyclodiphosphazanes, $[XP(\mu\text{-NR})]_2$ where X = halogen, hydroxyl, amino or thiol and R = aryl or alkyl, reported in the literature. Some selected examples are shown in *Fig. 1.2*.^{13–18} In general, cyclodiphosphazanes are known to be air- and moisture-sensitive. Their sensitivity can be attributed to the presence of trivalent phosphorus centers - highly susceptible to air and moisture – which can be readily oxidized to the phosphorus(V) species.

Figure 1.3. Examples of (a,b) cyclotriphosph(III)azanes (Type IX) and (c-f) cyclotetraphosph(III)azanes (Type X).^{20–24}

Apart from cyclodiphosphazanes, syntheses of larger P(III)-N ring systems (*e.g.*, cyclotriphosphazanes and cyclotetraphosphazanes) have been previously reported. However, there are comparatively fewer examples of the trimeric^{20,21} and tetrameric^{22–24} derivatives (*Fig. 1.3*). These larger cyclic compounds are also found to be highly air-sensitive as they are pyrophoric or rapidly decompose upon exposure to air, as described by Willey and co-workers.²⁴

1.1.1 - Dichlorocyclodiphosph(III)azanes

Figure 1.4. Iminophosphane (A) and, dimeric, trimeric and tetrameric cyclophosph(III)azanes (B-D).²⁵

There are many different classes of cyclophosph(III)azanes (where X = halogen, alkyl, aryl, amino, alkoxy or thiol), namely the dimeric (B), trimeric (C) and tetrameric forms (D) (*Fig. 1.4*).

Bond	Bond Energy (kJ·mol ⁻¹)
P(III)-N	290
C-C	346
C-O	358
C-N	305
C-S	272

Table 1.1. Bond energies of some covalent bonds.²⁶

These phosphorus(III)-nitrogen cyclic systems (**B - D**) are of particular interest since the P(III)-N bond energy (290 kJ·mol⁻¹) is comparable to that of their cyclic organic counterparts (Table 1.1).²⁶

Scheme 1.1. Synthesis of iminophosphane (**A**) where $X = \text{Cl}$ and $R = \text{Mes}^* = 2,4,6\text{-tri-}t\text{-butylphenyl}$.^{27,28}

To date, the only known derivative of chloroiminophosphane (**A**) that can be isolated as solid is $\text{ClP}=\text{NMe}^*$ ($\text{Mes}^* = 2,4,6\text{-tri-}t\text{-butylphenyl}$).^{27,28} The bulky substituent (Mes^*) on the imino nitrogen has been found to be essential to prevent cycloaddition from occurring (Scheme 1.1).

Scheme 1.2. Equilibrium between chloroiminophosphane (**A**) and dichlorocyclodiphosph(III)azane (**B**).²⁸

A slight reduction in the steric bulk of the substituent from Mes^* to either 2,6-diisopropylphenyl (Dipp) or 2,6-bis-(2,4,6-trimethylphenyl) (denoted as *m*-Ter for related publications) would allow the dimerization to take place, resulting in formation of dichlorocyclodiphosphazane (**B**) (Scheme 1.2).²⁸ This thus highlights the importance of the steric bulk of the substituents of the imino nitrogen on the formation of dichlorocyclodiphosph(III)azanes.

Scheme 1.3. Synthetic routes for formation of chlorocyclophosphazanes, [CIP(μ -NR)]_n.^{29–31}

Besides the dimerization reaction listed above (*Scheme 1.2*), there are a few other established synthetic strategies to generate dichlorocyclodiphosph(III)azanes. The methodologies are summarized in *Scheme 1.3*. Reacting organolithium reagents (*i.e.* lithium amide, RNHLi, or lithium silylamide, R¹N(SiR²₃)Li species) with equimolar amounts of phosphorus trichloride can lead to formation of chlorocyclophosph(III)azanes with elimination of lithium chloride as by-products (*Scheme 1.3a, b*).^{29–31} Alternatively, the reaction of phosphorus trichloride and equimolar amounts of primary amine in presence of triethylamine can also yield chlorocyclophosph(III)azanes (*Scheme 1.3c*). It has been documented that the triethylamine used can be replaced with primary amine, to achieve the same result (*Scheme 1.3d*). All these four synthetic routes proceed to form chlorocyclophosphazane along with elimination of by-products such lithium chloride, triethylammonium chloride, ammonium chloride and trialkylsilylchloride.

The reaction outcome of the four mentioned synthetic approaches depends greatly on several factors. These influencing factors are (i) the steric bulk of the substituents on the amine, (ii) concentration of the reagents involved and, (iii) the reaction temperature.¹⁹ It is important to emphasize the effect of the steric bulk (R) of the amine substituents, on the final ring size of the chlorocyclophosph(III)azane obtained (*i.e.* *n* in [CIP(μ -NR)]_n). It has been observed that when R is small (*e.g.*, methyl^{16,32} and ethyl^{20,24}), the formation of trimeric or tetrameric cyclophosphazane product (**C** and **D**) is favoured.

Conversely, if R is bulky (*e.g.*, *tert*-butyl), the reaction is likely to result in formation of dimeric cyclic arrangements (**B**) instead.^{30,33} Hence, it has been generally summarized that bulky amine substituents are required for the formation of dichlorocyclodiphosph(III)azanes.

Scheme 1.4. Reaction between PCl_3 and PhNH_2 to obtain bis(cyclodiphosph(III)azane) compound, $[(\text{PhHN})\text{P}(\mu\text{-NPh})_2\text{P}]_2(\mu\text{-NPh})$.³⁴

Apart from the steric bulk of the amine substituent, other factors such as concentration of reagents, ratio of the reagents and reaction conditions remain as important factors, influencing the type of product formed in the synthetic reactions. For instance, Thompson *et al.* reported that linear propagated cyclodiphosph(III)azane-based compound $[(\text{PhHN})\text{P}(\mu\text{-NPh})_2\text{P}]_2(\mu\text{-NPh})$ was obtained with the use of similar starting materials (*i.e.* phosphorus trichloride and aniline), but with slight modification to the reaction conditions and the mole ratio of reagents added (Scheme 1.4).³⁴

Figure 1.5. Various examples of dichlorocyclodiphosph(III)azanes reported to date.^{28,29,35–37}

To date, there have been a wide range of dichlorocyclodiphosph(III)azanes prepared and reported by various research groups over the past few decades. These dichlorocyclodiphosph(III)azanes bear varied endocyclic nitrogen substituents, ranging

from substituted phenyl (*e.g.*, Mes, Dipp and *m*-Ter *etc.*), pyridines to aliphatic substituents (*e.g.*, adamantyl *etc.*) are shown in Fig. 1.5.^{28,29,35–37}

Figure 1.6. Solid-state structures of *trans* dichlorocyclodiphosph(III)azanes, (a) $[CIP(\mu\text{-NTer})]_2$ and (b) $[CIP(\mu\text{-NMes}_F)]_2$.^{38,39}

Interestingly, dichlorocyclodiphosph(III)azanes are generally isolated in *cis* conformation in the solid-state as described by Stahl.⁴⁰ However, the Schulz group has recently succeeded in isolating *trans* dichlorocyclodiphosphazane, $[CIP(\mu\text{-NTer})]_2$, by increasing the steric bulk of the imino nitrogen to terphenyl group (Fig. 1.6a).³⁸ Roesky *et al.* reported on another example, *trans*- $[CIP(\mu\text{-NMes}_F)]_2$, obtained from the reaction of phosphorus trichloride with two equivalents of potassium amide, KNMes_F ($\text{Mes}_F = 2,4,6\text{-tris(fluoromethyl)aniline}$) in THF at 0 °C (Fig. 1.6b).³⁹

Despite numerous dichlorocyclodiphosphazanes reported, the *tert*-butyl derivative, [CIP(μ -N^{*t*}Bu)]₂ (**1.1**), remains as the simplest and the most extensively used one in studies of cyclodiphosphazane chemistry. Compound **1.1** is widely used due to its ease of synthesis and isolation as a solid by vacuum distillation. Such dichlorocyclodiphosphazanes have been widely employed in various research studies, ranging from synthetic building blocks for macromolecules,²⁶ larger inorganic frameworks^{41,42} and coordination polymers,^{43–45} catalysis^{46–49}, as well as biological applications.^{50–52}

1.1.2 - Monochlorocyclodiphosph(III)azanes

Figure 1.7. Examples of monochlorocyclodiphosph(III)azanes.^{53–55}

Another class of commonly used chlorocyclodiphosph(III)azanes is the monochloro derivatives, [CIP(μ -NR)₂P(NR¹R²)] (R = R¹ but not R² or, R $\neq$ R¹ and R², R¹ = R²). Some examples of monochlorocyclodiphosph(III)azanes are shown in Fig. 1.7.

Scheme 1.5. Synthetic route for formation of **1.2** using phosphorus trichloride, triethylamine and *tert*-butylamine.⁵³

Among the examples illustrated, only **1.2** can be readily prepared in a single step reaction from two equivalents of phosphorus trichloride, three equivalents of triethylamine and five equivalents of *tert*-butylamine at -78 °C (Scheme 1.5).⁵³ While the other monosubstituted cyclodiphosph(III)azane, [CIP(μ -

$\text{N}^i\text{Bu})_2\text{P}(\text{N}(\text{CH}_3)\text{C}(\text{O})(\text{NHCH}_3))$, was generated by controlled addition of one equivalent of *N,N'*-dimethylurea to a solution consisting of equimolar amounts of dichlorocyclodiphosph(III)azane **1.1**.⁵⁴ As for the last example, the monochlorocyclodiphosph(III)azane illustrated was obtained from a [2+2] cycloaddition of $[\text{ClP}=\text{NMes}^*]$ and $[(\text{N}^i\text{Pr}_2)\text{P}=\text{N}^i\text{Bu}]$.⁵⁵ Comparably, compound **1.2** can be synthesized with ease and hence has been commonly employed in the area of cyclodiphosphazane chemistry. Compound **1.2** serves as basic building block for synthesis of larger acyclic cyclodiphosphazane frameworks,⁵⁶ and it has also been further functionalized to produce asymmetric cyclodiphosphazane compounds.⁵⁷ Examples of such acyclic cyclodiphosphazane frameworks will be discussed in the later section (*Section 1.2.1 and 1.4*).

1.2 - Nucleophilic substitution reactions of dichlorocyclodiphosph(III)azanes

Dichlorocyclodiphosphazanes, $[\text{ClP}(\mu\text{-NR})]_2$, can readily undergo nucleophilic substitution reactions, replacing the Cl atoms with functional groups such as amines, alcohols or thiols to yield various disubstituted cyclodiphosph(III)azane derivatives.

Scheme 1.6. Various synthetic routes to obtain acyclic disubstituted cyclodiphosphazanes.^{40,58,59}

There are many acyclic disubstituted cyclodiphosph(III)azanes reported to date. They are typically obtained from nucleophilic substitution reactions of dichlorocyclodiphosph(III)azanes with monofunctional nucleophiles. These acyclic disubstituted cyclodiphosphazanes can be prepared *via* several established synthetic routes summarized in *Scheme 1.6*.^{40,58,59} The disubstituted cyclodiphosph(III)azanes

can be classified into two main categories: (i) Bis(amino)cyclodiphosph(III)azanes, and (ii) bis(alkoxy)cyclodiphosph(III)azanes. They are found to generally retain the air- and moisture-sensitivity from their parent dichlorocyclodiphosph(III)azanes, limiting their widespread applicability.⁶⁰

1.2.1 – Bis(amino)cyclodiphosph(III)azanes

Figure 1.8. Sub-categories of bis(amino)cyclodiphosph(III)azanes.

Bis(amino)cyclodiphosph(III)azanes can be further split into two sub-categories, namely the homosubstituted and heterosubstituted derivatives (Fig. 1.8).

Scheme 1.7. Synthetic route for homosubstituted bis(amino)cyclodiphosph(III)azanes, $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (**1.3**).^{61,62}

Homosubstituted bis(amino)cyclodiphosph(III)azanes refer to those bearing identical substituents on both the endocyclic and exocyclic nitrogen atoms. One such example is $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (**1.3**) which can be readily prepared by adding excess *tert*-butylamine dropwisely into a diluted solution of phosphorus trichloride at low temperature (Scheme 1.7).^{61,62} This synthetic procedure was known to result in high yield of the desired compound and was one of the earliest and easiest established route to gain access to such homosubstituted bis(amino)cyclodiphosph(III)azanes. The resulting ammonium chloride was filtered over Celite (P3) to obtain filtrate containing

the product which was then be purified by either recrystallization⁶¹ or vacuum distillation.⁶²

Heterosubstituted bis(amino)cyclodiphosph(III)azanes can be further classified into two smaller categories – symmetrical and asymmetrical heterosubstituted bis(amino)cyclodiphosph(III)azanes (*Fig. 1.8*).

Scheme 1.8. General synthetic routes for synthesis of symmetric heterosubstituted bis(amino)cyclodiphosph(III)azanes [(R²R¹N)P(μ-NR)]₂.

For symmetrical heterosubstituted bis(amino)cyclodiphosph(III)azanes, [(R²R¹N)P(μ-NR)]₂, they can be prepared from the nucleophilic substitution reactions of dichlorocyclodiphosph(III)azanes with two equivalents of either amine or lithium amide (*Scheme 1.8*).

Scheme 1.9. Representative scheme for asymmetric heterosubstituted cyclodiphosph(III)azanes.

For the case of asymmetric heterosubstituted cyclodiphosph(III)azanes, [(R¹R²N)P(μ-NR)P(NR³R⁴)], the synthesis typically requires two steps to produce the final product. The first step involves formation of monochlorocyclodiphosph(III)azane, [(R¹R²N)P(μ-NR)PCl], from first nucleophilic substitution on dichlorocyclodiphosph(III)azane (*Scheme 1.9*). The second step is second nucleophilic substitution using a different

amine – primary or secondary (NHR^3R^4) – to generate asymmetric heterosubstituted bis(amino)cyclodiphosph(III)azanes.

1.2.2 – Bis(alkoxy)cyclodiphosph(III)azanes

Moving on, another class of acyclic disubstituted cyclodiphosph(III)azanes that we would like to discuss is the bis(alkoxy)cyclodiphosph(III)azanes. Bis(alkoxy)cyclodiphosph(III)azanes ($[(\text{R}'\text{O})\text{P}(\mu\text{-NR})]_2$) are generally prepared in similar manner as symmetrical heterosubstituted bis(amino)cyclodiphosph(III)azanes, $[(\text{R}^2\text{R}^1\text{N})\text{P}(\mu\text{-NR})]_2$.

Scheme 1.10. General synthetic routes for preparation of bis(alkoxy)cyclodiphosph(III)azanes, $[(\text{R}'\text{O})\text{P}(\mu\text{-NR})]_2$.

The reactions of dichlorocyclodiphosph(III)azanes, $[\text{ClP}(\mu\text{-NR})]_2$, with alcohols or metal alkoxides lead to formations of bis(alkoxy)cyclodiphosph(III)azanes (Scheme 1.10). Dichlorocyclodiphosph(III)azanes are known to preferentially adopt the *cis* conformation over the *trans*, and this configuration is often retained after the nucleophilic substitution reactions. However, it has been reported by Koh *et al.* that the modification in synthetic condition(s) can selectively result in formation of a certain isomer of the desired bis(alkoxy)cyclodiphosph(III)azanes.⁵⁹

Scheme 1.11. Different synthetic routes to prepare different isomers of particular bis(alkoxy)cyclodiphosph(III)azanes.⁵⁹

Specifically, they reported that the reaction of compound **1.1** with 2,6-dimethylphenol in presence of triethylamine gave rise to exclusively *cis* isomer of desired product, *cis*-[(2,6-Me₂C₆H₃O)P(μ -N^tBu)]₂. Identical result was achieved when the phenol was replaced with sodium phenoxide, 2,6-Me₂C₆H₃ONa (Scheme 1.11). However, when lithium phenoxide, 2,6-Me₂C₆H₃OLi, was used, *trans* isomer (δ 214.8 ppm) was the only product formed, as confirmed by *in situ* ³¹P-¹H NMR spectroscopy (*cf.* *cis*: δ 156.3 ppm).

Scheme 1.12. Effect of endocyclic nitrogen substituents on the outcome of the reactions.

They have also investigated on the effect of endocyclic nitrogen substituents of the dichlorocyclodiphosph(III)azane on the conformation of bis(alkoxy)cyclodiphosph(III)azane obtained in the reactions. The study was conducted by reacting the same organic nucleophile (*i.e.* 4-methylphenol) with two different dichlorocyclodiphosph(III)azanes (*i.e.* [ClP(μ -N^tBu)]₂ and [ClP(μ -NPh)]₂). It was

observed that by replacing the *tert*-butyl group with a phenyl ring on the endocyclic nitrogen, instead of obtaining *cis* bis(alkoxy)cyclodiphosph(III)azane, the *trans* isomer was formed (*Scheme 1.12*). This therefore highlights the influence of the steric bulk of the endocyclic nitrogen substituent on the conformation of disubstituted cyclodiphosph(III)azanes formed in the reactions.

1.3 – Inorganic and hybrid cyclodiphosphazane-based macrocycles

Figure 1.9. Energy difference between the two isomers of dichlorocyclodiphosph(III)azanes.^{19,26}

Dichlorocyclodiphosph(III)azanes are known to exist in *cis/trans* equilibrium. The energy barrier of the *cis-trans* isomerization process of cyclodiphosph(III)azanes was calculated to be 4 – 40 kJ·mol⁻¹, with *cis* isomer being thermodynamically stable (*Fig. 1.9*).^{19,26} The preferred *cis* conformation of these dichlorocyclodiphosph(III)azanes has rendered their uses as building blocks for creation of macrocyclic arrangements.

Figure 1.10. Classification of inorganic and hybrid cyclodiphosphazane-based macrocycles.

Macrocyclic arrangements generated from dichlorocyclodiphosph(III)azanes can be classified into two different classes: inorganic and hybrid cyclodiphosphazane-based macrocycles. These macrocycles are differentiated by the bridging linkers between each two P₂N₂ units. Inorganic cyclodiphosphazane-based macrocycles refer to macrocycles

where the P_2N_2 units are bridged by inorganic linkers (Y) such as NR, O, S or Se. On the other hand, if the linker is an organic group (LL'), then the macrocycles are classified as hybrid cyclodiphosphazane-based macrocycles (Fig. 1.10).

1.3.1 – Inorganic cyclodiphosphazane-based macrocycles

Scheme 1.13. Synthetic scheme for formation of 'double-decked' inorganic cyclodiphosph(III)azane-based cage, $[P(\mu-N^iPr)_2P(\mu-N^iPr)]_2$.¹¹

One of the pioneering work on inorganic cyclodiphosph(III)azane-based macrocycles is the 'double-decked' molecular cages, $[P(\mu-NR)_2P(\mu-NR)]_2$. The first example of such inorganic macrocycles is $[P(\mu-N^iPr)_2P(\mu-N^iPr)]_2$ which was reported by Wolmerhäuser *et al.* in 1980 (Scheme 1.13).¹¹ This 'double-decked' compound was synthesized by refluxing monochlorocyclodiphosphazane, $[ClP(\mu-N^iPr)P(N(SiMe_3)^iPr)]$, in ACN for 15 hours and crystallized to afford the product in 25 % yield.

Scheme 1.14. Synthetic route of 'double-decked' inorganic cyclodiphosph(III)azane-based cage, $[P(\mu-N^tBu)_2P(\mu-N^tBu)]_2$.⁶³

The *tert*-butyl derivative, $[P(\mu-N^tBu)_2P(\mu-N^tBu)]_2$, was first detected in the adduct $[LiP(\mu-N^tBu)]_4 \cdot 0.25[P(\mu-N^tBu)_2P(\mu-N^tBu)]_2$ obtained from the reaction of $[(^tBuHN)P(\mu-N^tBu)]_2$ and *n*-butyllithium by Chivers *et al.*⁶³ They then reported their strategy to prepare this cage molecule, $[P(\mu-N^tBu)_2P(\mu-N^tBu)]_2$, as reaction of compound **1.1** with $[(^tBu(Li)N)_2P(\mu-N^tBu)]_2 \cdot 2THF$ in toluene (Scheme 1.14).⁶³

Scheme 1.15. Synthesis of inorganic cyclodiphosph(III)azane-based cage with phosphine linker, $[P(\mu\text{-N}^t\text{Bu})_2P(\mu\text{-PSiMe}_3)]_2$.⁶⁴

The reaction of compound **1.1** with equimolar amount of $\text{LiP}(\text{SiMe}_3)_2 \cdot 2\text{THF}$ in hexane at room temperature has led to formation of an analogous macrocycle, $[P(\mu\text{-N}^t\text{Bu})_2P(\mu\text{-PSiMe}_3)]_2$, bridged by phosphine group (Scheme 1.15).⁶⁴

Scheme 1.16. Synthesis of dimeric *O*-bridged cyclodiphosph(III)azane-based macrocycle, stabilized by CuCl .⁶⁵

The Wright group reported the syntheses of *O*-bridging cyclodiphosphazane-based macrocycles, $[P(\mu\text{-NR})_2P(\mu\text{-O})]_n$, adding to the then-known *NR*- and *P(SiMe3)*-bridging ‘double-decked’ macrocycles. They first described the preparation of dimeric *O*-bridged P_2N_2 macrocycle, $[(\text{ClCu})P(\mu\text{-N-2-C}_5\text{H}_4)_2P(\text{CuCl})(\mu\text{-O})]_2$. Controlled hydrolysis was performed by addition of stoichiometric amount of water (in pyridine) into a mixture containing dichlorocyclodiphosphazane, $[\text{ClP}(\mu\text{-N-2-C}_5\text{H}_4)]_2$, and two equivalents of CuCl at room temperature, to obtain the dimeric macrocycle (Scheme 1.16).⁶⁵

Scheme 1.17. Synthetic procedure for inorganic cyclodiphosph(III)azane-based cage, $[P(\mu\text{-N}^t\text{Bu})_2P(\mu\text{-O})]_4$.⁶⁶

Moving forward, the group then reported the formation of tetrameric *O*-bridged cyclodiphosph(III)azane macrocycle, $[P(\mu\text{-N}^t\text{Bu})_2P(\mu\text{-O})]_4$.⁶⁶ The tetrameric *O*-bridged macrocycle was prepared in stepwise manner. The first step of the synthesis involved controlled hydrolysis of compound **1.1** in THF by addition of water in presence of triethylamine at $-78\text{ }^\circ\text{C}$. The reaction mixture was warmed up to $5\text{ }^\circ\text{C}$ for 10 minutes and cooled back down to $-78\text{ }^\circ\text{C}$ for subsequent deprotonation to generate the lithium salt which was further reacted with another equivalent of **1.1** to yield the tetrameric *O*-bridged cyclic compound (*Scheme 1.17*).⁶⁶

Figure 1.11. Tetrameric and pentameric *NH*-bridged cyclodiphosph(III)azane-based macrocycles.⁶⁷

Beside the *O*-bridged cyclodiphosphazane macrocycles obtained, Wright *et al.* also described the syntheses of *NH*-bridged macrocycles (*Fig. 1.11*).^{67–70} These macrocyclic compounds were obtained from the reaction of $[(\text{H}_2\text{N})P(\mu\text{-N}^t\text{Bu})]_2$ with $[\text{ClP}(\mu\text{-N}^t\text{Bu})]_2$ in 1:1 molar ratio along with presence of triethylamine to result in the isolation of both tetrameric and pentameric inorganic macrocycles. The latter pentameric compound, $[(\mu\text{-NH})P(\mu\text{-N}^t\text{Bu})_2P]_5 \cdot \text{HCl} \cdot \text{THF}$, was recrystallized as a host-guest complex where a Cl^- ion was encapsulated within the cavity *via* hydrogen-bond interactions with five N-H protons of the macrocycle.

Scheme 1.18. Reaction route to obtain cyclodiphosph(V)azane-based macrocyclic arrangements.⁷¹

Inorganic cyclodiphosphazane-based macrocycles, bridged by chalcogenide, had also been described. These macrocycles were prepared in significantly different synthetic procedures as compared to their *NH*-, *NR*- and *O*-bridged analogs. Chivers and co-workers reported the preparation of various macrocyclic arrangements bearing $P^V_2N_2$ units. An example is trimeric macrocyclic arrangement bridged by *E-E* unit ($E = S$ or Se).⁷¹ This $P^V_2N_2$ compound was obtained from oxidation reaction of sodium or potassium salt of $[(t\text{-BuN})(E)P(\mu\text{-}N^t\text{Bu})_2P(E)(N^t\text{Bu})]^{2-}$ with I_2 in toluene or THF (Scheme 1.18).⁷¹ Following the successful isolation of this macrocycle, the group also reported on the reactions of sodium salts of $[(t\text{-BuN})(E)P(\mu\text{-}N^t\text{Bu})_2P(E)(N^t\text{Bu})]^{2-}$ with several gold(I) complexes.⁴¹

Scheme 1.19. Synthesis of the trimeric Au(I) cyclodiphosphazane macrocycle.⁴¹

Particularly, it is worth highlighting the reaction of sodium salt of $[(^t\text{BuN})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{Se})(\text{N}^t\text{Bu})]^{2-}$ with $\text{AuCl}\cdot\text{THT}$ in toluene at $-78\text{ }^\circ\text{C}$ led to formation of analogous trimeric macrocyclic arrangement (*Scheme 1.19*).⁴¹ The isolated trimeric gold(I) macrocycle was formed by *Se-Au-Se* bridging units between two $\text{P}^{\text{V}}_2\text{N}_2$ rings. It was seen as formal insertion of Au(I) into the *Se-Se* bridges of the ‘gold-free’ trimeric analog seen in *Scheme 1.18*, except that none of the exocyclic nitrogen in the latter was protonated.⁴¹

Figure 1.12. Examples of chalcogen-bridged cyclodiphosphazane-based macrocycles.⁷²

On the other hand, Wright and co-workers have also been exploring synthetic methodologies to generate inorganic cyclodiphosphazane macrocycles over the past decades.^{42,73–75} Recently, they described the formation of hexameric *Se*-bridged macrocycle, which was also a mixed valent compound. The *Se*-bridged macrocycle was obtained from the reaction of $[\text{H}(\text{S})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ with NaBn and elemental selenium, followed by addition of compound **1.1**.⁷² While, the trimeric macrocycle, bearing *Se-Se* bridges, was prepared using similar procedure as that by Chivers *et al.* mentioned earlier - replacing the starting material $[(^t\text{BuN})(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2\cdot 2\text{Na}(\text{THF})_2$ with $[\text{S}(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})]_2\cdot 2\text{Na}$. The reaction illustrated the preference for Se as the bridging atom over S, which was proposed to be due to the presence of longer P-Se bond leading to a lower net steric/electronic congestion of the peripheral *tert*-butyl and S-groups.⁷²

1.3.2 – Hybrid cyclodiphosphazane-based macrocycles

Other than inorganic cyclodiphosphazane macrocycle, dichlorocyclodiphosphazanes can also react with numerous bifunctional organic nucleophiles to give rise to hybrid cyclodiphosphazane macrocycles, $[LL'P(\mu-NR)]_n$ (LL' = bifunctional organic linkers and n = the number of repeating unit). Herein, we presented some reported examples of hybrid macrocycles obtained over the past few years.

Scheme 1.20. Synthetic routes of hybrid cyclic compounds prepared from dichlorocyclodiphosphazanes.^{76–78}

Prior to 2003, the only known examples were monomeric species ($n = 1$) with basket-like structure in which only one LL' spacer linking the ends of the same P_2N_2 ring. Examples are monomeric cyclic compounds, $[P(\mu-NR)_2P][\mu-O(CH_2)_3O]$ ($R = ^tBu$ or Ph) obtained exclusively from the reactions of dichlorocyclodiphosphazanes with one equivalent of 1,3-propanediol (Scheme 1.20).⁷⁶ It was later discovered that by introducing methyl groups on the organic linker, the reaction resulted in formation of dimeric macrocycle ($n = 2$), $[(P(\mu-N^tBu)_2P)(\mu-OCH_2C(CH_3)_2CH_2O)]_2$, as a minor product.^{77,78} These results therefore illustrated the effect of steric bulk of the organic linkers on the reaction outcomes.

To date, there are various studies discussing the possible factors affecting the reaction products. These studies have illustrated that the reaction conditions (*e.g.*, reaction solvents and/or temperature) and the identity of the organic linkers employed have effects on the products formed.^{56,78,79}

Scheme 1.21. Solvent effect on the outcome for reaction of compound **1.1** and 1,2-diaminobenzene.⁷⁸

For example, the Wright group illustrated the effect of reaction conditions on the product(s) obtained from the reaction of compound **1.1** with 1,2-diaminobenzene (Scheme 1.21).⁷⁸ When the reaction was performed in refluxing THF, monomeric cyclic compound, [P(μ -N^tBu)₂P](μ -NHC₆H₄NH), was the only soluble phosphorus-containing compound detected on the *in situ* ³¹P-{¹H} NMR spectrum (δ 138.9 ppm). While, when the same reaction was carried out in toluene at room temperature, a mixture of monomeric and dimeric cyclic compounds was obtained as indicated by the presence of three resonance signals (δ 138.0, 123.7 and 103.1 ppm) on the ³¹P-{¹H} NMR spectrum.⁷⁸ These results showed that the reaction solvent and temperature can lead to formation of different reaction products.

Figure 1.13. Dimeric and tetrameric cyclodiphosph(III)azane-based macrocycles obtained from compound **1.1** and 1,3-dihydroxybenzene.⁵⁶

On the other hand, Balakrishna and co-workers have showed that the mixture of reaction products obtained could be due to the nature of the organic linkers used. Specifically,

they described the reaction of compound **1.1** with 1,3-dihydroxybenzene had led to formation of mixture of cyclic cyclodiphosph(III)azane compounds – dimeric and tetrameric (*Fig. 1.13*).⁵⁶

Apart from working with symmetrical bifunctional organic linkers, there are several reactions reported with the use of asymmetric organic linkers. These reactions between dichlorocyclodiphosph(III)azanes and asymmetric organic linkers have the possibility to give rise to mixture of products which may comprise of isomeric products (*i.e. cis* and *trans* dimeric macrocycles).

*Scheme 1.22. Formation of trans- and cis-macrocycles obtained from reactions of compound 1.1 and 2-aminophenol and 2-aminothiophenol, respectively.*⁷⁹

Examples of such cases are the reactions of compound **1.1** with (i) 2-aminophenol and (ii) 2-aminothiophenol in THF using triethylamine as Bronsted base reported by Wright and co-workers (*Scheme 1.22*).⁷⁹ It was found that the *cis* isomer of $[(\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\mu\text{-NHC}_6\text{H}_4\text{O}))_2]$ and *trans* isomer of $[(\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\mu\text{-NHC}_6\text{H}_4\text{S}))_2]$ were observed as the major products in their respective reactions, indicated by the $^{31}\text{P}\{-^1\text{H}\}$ and ^1H NMR spectroscopic studies recorded.

Scheme 1.23. (a) Synthesis of acyclic disubstituted compounds, and (b) thermal rearrangement of $[(H_2NC_6H_4S)P(\mu-N^tBu)]_2$.⁷⁹

Ab initio calculations were carried out and suggested that the bias towards the respective isomers is not thermodynamically driven, but rather kinetics. Experimental studies were then performed to further validate the hypothesis of kinetic control in these reactions. The group proceeded to first synthesize the disubstituted cyclodiphosph(III)azane, $[(H_2NC_6H_4S)P(\mu-N^tBu)]_2$, by reacting one equivalent of **1.1** with two equivalents of 2-aminothiophenol (Scheme 1.23a). The acyclic disubstituted cyclodiphosph(III)azane was then heated and observed to undergo intramolecular rearrangement to form the asymmetrical analog and cyclic monomer (Scheme 1.23b). This thermal rearrangement therefore further supported the proposal of the selectivity of *trans*- $[P(\mu-N^tBu)_2P(\mu-NHC_6H_4S)]_2$ to be kinetic-driven.

1.4 - Bis(cyclodiphosphazane) derivatives

The previous sections focused mainly on the reactions involving the use of dichlorocyclodiphosph(III)azane, $[ClP(\mu-N^tBu)]_2$ (**1.1**). The monochloro cyclodiphosph(III)azane, $[(^tBuN)P(\mu-N^tBu)_2PCl]_2$ (**1.2**), is also utilized in the research of cyclodiphosphazanes, albeit to a smaller extent. Compound **1.2** is commonly used to form larger acyclic compounds *via* nucleophilic substitution of the remaining chlorine substituent. Congruent to the classification mentioned in earlier sections, the

nucleophilic substitution reactions on compound **1.2** can lead to reaction products which can also be classified into two categories, namely (i) inorganic and (ii) organic bridging spacer.

1.4.1 - Bis(cyclodiphosph(III)azane) derivatives with inorganic linker

Scheme 1.24. Examples of bis(cyclodiphosph(III)azane) derivatives with inorganic linker.⁸⁰

Prior to 2001, only two examples of bis(cyclodiphosph(III)azane) frameworks were reported (Scheme 1.24). Compound **1.2** was used as precursor to generate disubstituted cyclodiphosph(III)azane, [(^tBuHN)P(μ -N^tBu)₂P(NH₂)] (**1.4**), which was further reacted to yield the two compounds illustrated.⁸⁰ When compound **1.4** was reacted with tris(dimethylamido)antimony(III), the reaction led to formation of inorganic bis(cyclodiphosphazane) compound, [(^tBuHN)P(μ -N^tBu)₂P(μ -N(SbNMe₂))]₂ – bridged by a Sb₂N₂ ring. On the other hand, when two equivalents of **1.4** was reacted with six equivalents of *n*-butyllithium, trianionic cyclodiphosphazane-based species was formed.⁸⁰

Scheme 1.25. Synthesis of O-bridged bis(cyclodiphosph(III)azane) compound.⁸¹

Adopting the same strategy employed in the synthesis of *O*-bridged macrocycles, Wright and co-workers reported on the preparation of *O*-bridged bis(cyclodiphosph(III)azane) derivative, [(^tBuHN)P(μ -N^tBu)₂P]₂(μ -O) from compound **1.2**. Controlled hydrolysis was first performed on compound **1.2**, followed by deprotonation of P-H and lastly addition of another equivalent of **1.2** to yield the desired compound (*Scheme 1.25*).⁸¹

1.4.2 - Bis(cyclodiphosph(III)azane) derivatives with organic linkers

Compared to the inorganic counterparts, the syntheses of hybrid bis(cyclodiphosph(III)azane) compounds are relatively simpler. These hybrid bis(cyclodiphosph(III)azane) compounds can be obtained by simply reacting two equivalents of compound **1.2** with one equivalent of bifunctional organic linkers.

*Scheme 1.26. Reaction of **1.2** with ethylene glycol to obtain hybrid bis(cyclodiphosph(III)azane) compound.*⁸²

However, to the best of our knowledge, the examples reported are limited to that obtained from the reactions involving compound **1.2** with aliphatic and aromatic diols. An example of such bis(cyclodiphosph(III)azane) compounds is [(^tBuHN)P(μ -N^tBu)₂P]₂(μ -OCH₂CH₂O) prepared in the reaction of **1.2** with ethylene glycol (*Scheme 1.26*).⁷⁸

Figure 1.14. Examples of bis(cyclodiphosph(III)azane) compounds bridged by organic linkers.^{56,77,83}

Other examples of such frameworks were prepared with bifunctional organic linkers such as 2,2-diethyl-1,3-propanediol and 1,3-dihydroxybenzene (*Fig. 1.14*).^{56,77,83}

1.4.3 - Other inorganic bis(cyclodiphosphazane) compounds

Beside preparing such bis(cyclodiphosphazane) frameworks from compound **1.2**, there are some examples of structural similar cyclodiphosphazane compounds obtained by other synthetic means.

Scheme 1.27. Formations of O- and S-bridged bis(cyclodiphosph(III/V)azane) compounds.^{84,85}

The Wright group reported on two examples of mixed valent, bis(cyclodiphosphazane) frameworks as shown in *Scheme 1.27*. Despite being analogous to each other, these two compounds were isolated from reactions of different synthetic approaches. The *O*-bridged derivative, [H(O)P(μ -N^tBu)₂P]₂(μ -O), was obtained from controlled hydrolysis of compound **1.1** along with presence of minor contaminant, [H(O)P(μ -N^tBu)]₂.⁸⁴ While the *S*-bridged derivative, [H(S)(P(μ -N^tBu)₂P)]₂(μ -S) was observed from prolonged storage of monomeric cyclic cyclodiphosph(III)azane compound, [(μ -S(SnPh₂)S)(P(μ -N^tBu)₂P)], in THF at room temperature.⁸⁵

On the other hand, Chivers and co-workers systematically designed synthetic approaches to generate such bis(cyclodiphosphazane) frameworks, stemming from the use of lithium cyclodiphosph(V)azane dichalcogenides (*e.g.*, Li[(^tBuN)(E)P(μ -

$\text{N}^t\text{Bu})_2\text{P}(\text{NH}^t\text{Bu})](\text{THF})_2$ ($\text{E} = \text{S}, \text{Se}$ or Te) or $[\text{Li}(\text{TMEDA})]_2[(^t\text{BuN})(\text{Te})\text{P}(\mu\text{-N}^t\text{Bu})]_2$.

Some examples of the synthesized inorganic bis(cyclodiphosphazane) frameworks by the Chivers group are described as follows.

Scheme 1.28. Synthesis of *Te-Te* bridged bis(cyclodiphosph(V)azane) compound.⁸⁶

The oxidation by I_2 on lithium cyclodiphosph(V)azane dichalcogenide, $[\text{Li}(\text{TMEDA})]_2[(^t\text{BuN})(\text{Te})\text{P}(\mu\text{-N}^t\text{Bu})]_2$, has resulted in the formation and isolation of extremely sensitive black crystals of *Te-Te* bridged bis(cyclodiphosph(V)azane) framework (Scheme 1.28).

Scheme 1.29. Redox reactions of tellurium tetrachloride with lithium bis(*tert*-butyl)cyclodiphosph(V)azanes.⁸⁷

Utilizing the monoanionic species, $\text{Li}[(^t\text{BuN})(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{E})(\text{NH}^t\text{Bu})](\text{THF})_2$, Chivers *et al.* reported on a series of reactions conducted with tellurium tetrachloride, TeCl_4 , with varied reaction conditions.⁸⁷ Depending on the reaction duration, different bis(cyclodiphosph(V)azane) frameworks were isolated (Scheme 1.29). When the monoanionic bis(*tert*-butylamido)cyclodiphosph(V)azane species was reacted with half-molar equivalent of TeCl_4 , the tellurium(IV) was reduced to tellurium(II) and

stabilized by the dative bond from the chalcogen atom of two P₂N₂ units. Increasing the molar ratio of 4:1, the tellurium(IV) was also reduced to tellurium(II). However, in this case, the tellurium(II) center was bonded by two anionic cyclodiphosph(V)azane *via* the delocalization of negative charge over N-P-E moiety (*Scheme 1.29*).

1.5 - Oxidation of phosphorus(III) centers

Phosphorus is known to exist as two possible oxidation states (III and V). Cyclodiphosph(III)azanes are generally highly sensitive towards air and moisture as they can get readily oxidized to phosphorus(V) species. In most cases, the oxidation and/or hydrolysis to phosphorus(V) species - which causes a change in geometry, overall structural motif and integrity of the molecule – is/are not desired. However, synthetic methods have been successfully developed to generate the corresponding cyclodiphosph(V)azanes by oxidizing with appropriate oxidants (*e.g.*, elemental chalcogen and hydroperoxides) or hydrolyzing in a controlled manner of the parent cyclodiphosph(III)azanes. The resulting partial and fully oxidized cyclodiphosphazanes are found to exhibit unique coordination properties and varied degree of improved air- and moisture-stability. In addition, they are employed as building blocks for supramolecular system.^{88,89}

1.5.1 - Oxidation of dichlorocyclodiphosph(III)azane (1.1)

Scheme 1.30. Oxidation of compound 1.1 to obtain dichlorocyclodiphosph(V)azanes, [Cl(E)P(μ-N^tBu)]₂.^{75,90,91}

As dichlorocyclodiphosph(III)azanes are typically highly sensitive towards air and moisture, their syntheses and subsequent manipulations need to be conducted under

strict exclusion of water and oxygen environments. Oxidation reactions on dichlorocyclodiphosph(III)azane **1.1** were carried out to obtain the corresponding cyclodiphosph(V)azanes, $[\text{Cl}(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (Scheme 1.30).^{75,90,91} These oxidation reactions yielded mixtures of *cis* and *trans* oxidized products, despite the use of only *cis*-**1.1**. The dichlorocyclodiphosph(V)azanes exhibited varied degree of air and moisture-stabilities. The oxide and sulfide, $[\text{Cl}(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ where E = O and S respectively, were extremely stable in air and water. While the selenide, $[\text{Cl}(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})]_2$, retained the sensitivity towards oxygen and moisture.

Scheme 1.31. Reactions of dichlorocyclodiphosph(V)azane with 4-hydroxybenzonitrile.⁹¹

The enhanced stabilities towards air and moisture were desired, however, it came with an expense of reactivity of the compounds. The oxide and sulfide derivatives were later discovered to be unreactive when used as replacement for compound **1.1** in nucleophilic substitution reactions. For instance, our group attempted to access bis(alkoxy)cyclodiphosph(V)azane directly from oxidized dichlorocyclodiphosph(V)azanes, $[\text{ClP}(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ where E = O and S, and 4-hydroxybenzonitrile, but found it to be unachievable (Scheme 1.31). While the air- and moisture-sensitive selenide, $[\text{ClP}(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})]_2$, was the only dichlorocyclodiphosph(V)azane to successfully furnish the corresponding bis(alkoxy)cyclodiphosph(V)azane (Scheme 1.31).⁹¹

Scheme 1.32. Formation of hexameric cyclodiphosph(III/V)azane-based macrocycle.^{74,75}

However, the Wright group reported Wurtz coupling reactions of both the sulfide and selenide, $[\text{Cl}(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ where $\text{E} = \text{S}$ and Se , with sodium metal to give hexameric mixed valent, E -bridged macrocycles, $[(\text{E})\text{P}^{\text{V}}(\mu\text{-N}^t\text{Bu})\text{P}^{\text{III}}(\mu\text{-E})]_6$ (Scheme 1.32).^{74,75} The formation of S -bridged hexameric macrocycle hence highlights that with appropriate reducing agent, it was possible to further manipulate the air and moisture-stable dichlorocyclodiphosph(V)azane sulfide, $[\text{ClP}(\text{S})\text{P}(\mu\text{-N}^t\text{Bu})]_2$.

1.5.2 - Oxidation of bis(amino)- and bis(alkoxy)cyclodiphosph(III)azanes

Scheme 1.33. General solution-based oxidation scheme to obtain cyclodiphosph(V)azanes.

Bis(amino)- and bis(alkoxy)cyclodiphosph(V)azanes can be prepared by reacting their respective parent compounds with appropriate oxidising agents such as peroxides or elemental chalcogen. There is an extensive library of such acyclic disubstituted cyclodiphosph(V)azanes generated by these synthetic approaches (Scheme 1.33). One of the earliest reported examples of acyclic disubstituted cyclodiphosph(V)azanes is $[(^t\text{BuHN})(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ where $\text{E} = \text{O}, \text{S}$ or Se . The oxidation reactions of

bis(amino)cyclodiphosph(III)azane, $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (**1.3**), were reported by Norman, Chivers and Stahl on separate occasions.^{92–94} The reactions were conducted on *cis*- $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (**1.3**) and resulted in formation of either mainly or exclusively the *cis*-oxidized products. Analogous oxidations were also performed on bis(alkoxy)cyclodiphosphazanes to obtain the corresponding oxidized products. Differed from the results observed in oxidations of $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (**1.3**), our group observed formation of *cis/trans* mixtures for the oxidation reactions carried out on *cis*- $[(p\text{-OC}_6\text{H}_4\text{CN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (Scheme 1.33).⁹¹

1.5.3 - Oxidation of inorganic cyclodiphosphazane-based macrocycles

Scheme 1.34. Oxidation of hexameric cyclodiphosphazane-based macrocycle, $[(\mu\text{-S})(\text{S})\text{P}^{\text{V}}(\mu\text{-N}^t\text{Bu})\text{P}^{\text{V}}(\text{S})(\mu\text{-S})\text{P}^{\text{III}}(\mu\text{-N}^t\text{Bu})\text{P}^{\text{III}}]_3$.⁷²

Analogous oxidation reactions were also carried out on various inorganic P_2N_2 -based macrocycles. For instance, Wright *et. al* reported the oxidation of mixed valent, hexameric inorganic cyclodiphosphazane macrocycle, $[(\mu\text{-S})(\text{S})\text{P}^{\text{V}}(\mu\text{-N}^t\text{Bu})\text{P}^{\text{V}}(\text{S})(\mu\text{-S})\text{P}^{\text{III}}(\mu\text{-N}^t\text{Bu})\text{P}^{\text{III}}]_3$, with elemental sulfur in refluxing toluene to obtain the phosphorus(V) derivative, $[(\mu\text{-S})(\text{S})\text{P}^{\text{V}}(\mu\text{-N}^t\text{Bu})\text{P}^{\text{V}}(\text{S})]_6$ (Scheme 1.34).⁷² The resulting hexameric macrocycle was found to exhibit enhanced air- and hydrolytic-stabilities in wet acetone – extension of our observation of improved stability towards air and moisture upon oxidation.⁹¹

Scheme 1.35. Oxidation of 'double-decked' inorganic macrocycles resulted in C-N bond cleavage.^{95,96}

Recently, our group reported the oxidation reactions of 'double-decked' inorganic macrocycles, $[P(\mu\text{-N}^t\text{Bu})_2P(\mu\text{-N}^t\text{Bu})]_2$ (**1.5**) and $[P(\mu\text{-N}^i\text{Pr})_2P(\mu\text{-N}^i\text{Pr})]_2$ (**1.6**) (Scheme 1.35).^{95,96} Oxidation with excess elemental selenium was first carried out on compound **1.5** and monitored by *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy. It would be expected to observe a singlet resonance signal for the fully oxidized derivative, $[(\text{Se})P(\mu\text{-N}^t\text{Bu})_2P(\text{Se})(\mu\text{-N}^t\text{Bu})]_2$, within the range of δ 0 – 50 ppm for typical cyclodiphosph(V)azane derivatives reported (e.g. $[(\text{Se})P(\mu\text{-N}^t\text{Bu})_2P(\text{Se})(\mu\text{-1,3-OC}_6\text{H}_4\text{O})]_2$ and *cis*- $[(\text{CyHN})(\text{Se})P(\mu\text{-N}^t\text{Bu})_2]_2$, δ 32.7 and 35.4 ppm, respectively).^{56,88} However, the *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum revealed two sets of multiplet resonance signals at $\delta \sim 24$ and ~ 22 ppm. Upon subsequent work-ups and successful isolation of diffraction quality single crystals, the product was found to be fully oxidized macrocycle, however with three of the *tert*-butyl groups cleaved (Scheme 1.35a). The cleavage of the N-*t*Bu bonds resulted in formation of new N-H bonds which was further confirmed by the presence of two broad singlets at δ 5.64 and 4.28 ppm on the ^1H NMR spectrum. It was observed from the SC-XRD studies of the tetra-selenide macrocycle, $\text{P}_4(\mu\text{-N}^t\text{Bu})_3(\mu\text{-NH})_3\text{Se}_4$, that the P_4N_6 framework contracts upon oxidation, hence we proposed that the C-N bond cleavage observed was driven by the release of steric strain.

In order to validate this proposal, less sterically hindered ‘double-decked’ macrocycle, $[P(\mu\text{-N}^i\text{Pr})_2P(\mu\text{-N}^i\text{Pr})]_2$ (**1.6**), was prepared. As **1.6** was thermodynamically unstable with respect to its adamantoid isomer, $[P_4(\text{N}^i\text{Pr})_6]$, milder oxidation reaction conditions were employed (*Scheme 1.35b*).⁹⁵ The *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy taken suggested formation of mixture of products comprised of partially oxidized species and a fully oxidized derivative, $P_4(\mu\text{-N}^i\text{Pr})_5(\mu\text{-NH})\text{Se}_4$, which one of the *iso*-propyl groups was cleaved. Further spectroscopic characterization on the isolated product corroborated the identity of the fully oxidized derivative as $P_4(\mu\text{-N}^i\text{Pr})_5(\mu\text{-NH})\text{Se}_4$.⁹⁶ This therefore supported the cleavage of C-N bonds upon oxidation of $[P(\mu\text{-NR})_2P(\mu\text{-NR})]_2$ with elemental selenium was driven by the release of steric strain on the P_4N_6 frameworks.

1.5.4 - Oxidation of hybrid cyclodiphosph(III)azane-based macrocycles

Similar oxidation reactions can be also carried out on hybrid cyclodiphosph(III)azane-based macrocycles. However, despite the large volume of $P^{\text{III}}_2N_2$ -based hybrid macrocycles reported, the number of oxidized derivatives is considerably less. There is, in fact, no complete series of chalcogen-oxidized hybrid P_2N_2 -based macrocycles to date.

Scheme 1.36. Oxidation of hybrid cyclodiphosph(III)azane macrocycle with hydrogen peroxide or elemental selenium.^{56,97}

Balakrishna and co-workers reported oxidation reactions on several dimeric hybrid cyclodiphosphazane macrocycles.^{56,97} They performed oxidations on dimeric cyclodiphosphazane macrocycle, $[P(\mu\text{-N}^t\text{Bu})_2P(\mu\text{-1,3-OC}_6\text{H}_4\text{O})]_2$, obtained from the reaction of compound **1.1** with 1,3-dihydroxybenzene. The tetra-oxide, $[(O)P(\mu\text{-N}^t\text{Bu})_2P(O)(\mu\text{-1,3-OC}_6\text{H}_4\text{O})]_2$, was prepared from oxidising the macrocycle with hydrogen peroxide in THF at room temperature. While, the oxidation with elemental selenium was conducted in refluxing toluene for 1 day to yield the corresponding tetra-selenide, $[(\text{Se})P(\mu\text{-N}^t\text{Bu})_2P(\text{Se})(\mu\text{-1,3-OC}_6\text{H}_4\text{O})]_2$ (Scheme 1.36a). Recently, the group also reported similar oxidation reactions on the newly synthesized dimeric hybrid cyclodiphosphazane macrocycle, $[P(\mu\text{-N}^t\text{Bu})_2P(\text{O-}m\text{-C}_6\text{H}_4\text{CHNCH}_2)_2]_2$ to yield the corresponding tetra-oxide and tetra-selenide (Scheme 1.36b). In both occasions, only the selenides were successfully recrystallized and characterized by SC-XRD studies.

Scheme 1.37. Oxidation of dimeric hybrid cyclodiphosphazane macrocycle with elemental sulfur.⁹⁸

Swamy *et al.* reported on the oxidation of $[P(\mu\text{-N}^t\text{Bu})_2P(\mu\text{-OCH}_2\text{C}(\text{Me})_2\text{CH}_2\text{O})]_2$, with elemental sulfur in refluxing toluene to produce the corresponding tetra-sulfide macrocycle (Scheme 1.37).⁹⁸ To date, this is only example of sulfur-oxidized hybrid cyclodiphosphazane macrocycle reported.

1.6 - Applications of cyclodiphosphazanes

Cyclodiphosphazanes have been shown to exhibit positive results in many areas, validating the importance of continual exploration and developments of cyclodiphosphazane chemistry. For instances, these cyclodiphosphazane frameworks have been used as anionic or neutral ligands in transition metal chemistry^{99–101} and building blocks for supramolecular systems.^{84,89} They are found to exhibit promising use as anti-cancer drugs^{50–52} and in host-guest chemistry.^{67–70} In this section, we will highlight some of these applications to illustrate the need for further study in the area.

1.6.1 – Cyclodiphosphazanes in supramolecular chemistry

Dichlorocyclodiphosphazanes have been reacted with many primary amines to generate a family of bis(amino)cyclodiphosphazanes with the general formula of $[(\text{RHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$. Further oxidation has rendered these cyclodiphosphazanes to be more air- and hydrolytic-stable. With the improvement in stabilities towards air and moisture, it opens up more research opportunities for these cyclodiphosphazane compounds. For instance, our group recently reported the use of *cis*- $[(^t\text{BuHN})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ as a building block for supramolecular systems. *Cis*- $[(^t\text{BuHN})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ was previously reported with its x-ray crystal structure revealing the exocyclic N-H protons adapting *exo*, *endo* orientation. However, in the study that our group conducted, we successfully recrystallized the bis(*tert*-butylamido)cyclodiphosph(V)azane in acetone and its x-ray crystal structure showed an *exo*, *exo* conformation instead. Exploiting this conformation, a series of different polarity solvents and solvent combination were screened to determine which solvate crystals of *cis*- $[(^t\text{BuHN})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ would form and how the packing motif would differ. It was then concluded that solvents bearing polar functionality that can act as hydrogen bond acceptor are suitable solvents for formation

of solvate crystals. The solvate crystals obtained from MeOH, ACN, DMSO, DMF and acetone consisted of identical intermolecular $R^2_1(8)$ hydrogen bonding motif. The motif was formed by the hydrogen bond interaction between the exocyclic N-H of the cyclodiphosph(V)azane with the electronegative O or N of solvate molecule (*Fig. 1.15*).

Figure 1.15. Cocrystallization of *cis*-[(*t*BuHN)(Se)P(μ -N^{*t*}Bu)]₂ with different solvents.⁸⁹

Next, we explored the use of organic compounds that have hydrogen bond donor and/or acceptor (*i.e.* 1,1,3,3-tetramethylguanidine (TMG) and *N,N'*-dimethylurea (DMU)), to form supramolecular systems with *cis*-[(*t*BuHN)(Se)P(μ -N^{*t*}Bu)]₂. The diffraction quality crystals were obtained from slow evaporation of solution mixtures of *cis*-[(*t*BuHN)(Se)P(μ -N^{*t*}Bu)]₂ and the organic compound. For example, in the case of DMU, two different polymorphs comprising of stoichiometric ratio of 1:1 of the two components were obtained from MeOH and CHCl₃ solutions. The two polymorphs were hydrogen bonded chains, illustrating presence of different intermolecular hydrogen bond interactions. Beside forming intermolecular hydrogen bonding to assemble into supramolecular systems, the cyclodiphosph(V)azane was also capable of interacting with 1,4-dibromotetrafluorobenzene (DBTFB) *via* halogen bond to give cocrystals of stoichiometric ratio 1:1 of the two compounds. The cocrystals formed were halogen-bonded, zig-zag chains, illustrating the halogen bifurcated interaction of the *endo*-Se with Br of two molecules of DBTFB, and *exo*-Se $\cdots\pi$ interaction. All these cocrystals obtained hence demonstrated the versatility and robustness of cyclodiphosph(V)azane scaffold as building unit in supramolecular chemistry.⁸⁹

1.6.2 – Reactions of cyclodiphosphazanes and metal chlorides

Bis(amino)cyclodiphosph(III)azanes, $[(\text{RHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$, have been deprotonated to generate the dianionic species, $[(\text{RN})\text{P}(\mu\text{-N}^t\text{Bu})]_2^{2-}$. These dianionic cyclodiphosph(III)azane derivatives were reacted with many metal chlorides and resulted in different metal-cyclodiphosph(III)azane frameworks.

Scheme 1.38. Synthetic scheme to generate group 4 metal bis(amino)cyclodiphosphazane complexes.^{46,102,103}

To date, there are numerous reactions between group 4 metal complexes and cyclodiphosphazane reagents being reported.^{18,46,102–105} The first examples of transition-metal bis(amino)cyclodiphosphazane complexes were described by Stahl *et al.* back in 1997 – reacting the lithiated bis(*tert*-butyl)cyclodiphosph(III)azane with hafnium(IV) and zirconium(IV) chloride. These complexes were found to be thermally and chemically stable – being unaffected from the attempted oxidations with oxygen and sulfur in refluxing toluene for 12 hours (Scheme 1.38).¹⁰³ It was only until recently that the group successfully obtained the phosphorus(V) analogs after prolong reflux of these complexes with excess sulfur for 5 days.⁴⁶ With these group 4 bis(amino)cyclodiphosphazane complexes in hand, they further investigated on the catalytic abilities of these complexes. Combined with methaluminoxane (MAO), the complexes form very active catalyst for polymerization of ethylene. It was then observed that, under the same conditions for the catalysis reaction, the zirconium bis(amino)cyclodiphosph(V)azane complex was approximately seven times as productive as its phosphorus(III) counterpart. These results highlight the potential use

of cyclodiphosphazanes as ligands for transition metals, which can be further employed in catalysis chemistry.

Scheme 1.39. Reactions of dianionic bis(tert-butyl)cyclodiphosph(III)azane with group 13 metal chlorides.^{40,106}

These bis(amino)cyclodiphosph(III)azanes were found to be reactive towards group 13 metal chlorides as well. The reactions of aluminium(III) and gallium(III) trichlorides with dianionic cyclodiphosph(III)azane, $[(\text{'BuN})\text{P}(\mu\text{-N'\text{'Bu}})]_2^{2-}$, resulted in heterobicyclic mononuclear complexes (Scheme 1.39).⁴⁰ When lithium bis(amino)cyclodiphosph(III)azane, $[\text{Li}(\text{thf})(\text{RN})\text{P}(\mu\text{-N'\text{'Bu}})]_2$, was reacted with heavier group 13 metal chlorides (*i.e.* indium(I) and thallium(I) chlorides), the metal complexes obtained were structurally different. The reaction involving TlCl resulted in formation of dinuclear Tl(I) heterocube, resembling that of the starting lithium salt of $[(\text{'BuN})\text{P}(\mu\text{-N'\text{'Bu}})]_2^{2-}$. Whereas, when InCl was added to the dianionic species, a dimeric compound made up of mononuclear In(II) cages bridged by In-In bond was obtained.¹⁰⁶ The thallium(I) complex was extremely air-sensitive and darkened upon slightest exposure to oxygen, while the indium(II) dimer slowly decomposed in solution to result in formation of metallic indium.

Scheme 1.40. Syntheses of group 14 bis(tert-butyl)cyclodiphosph(III)azane compounds.^{107,108}

Stahl and co-workers have also reported the reactions of dianionic cyclodiphosph(III)azane with group 14 metal chlorides, such as SiCl_4 , GeCl_2 and SnCl_2 (Scheme 1.40).^{107,108} The reaction of silicon tetrachloride with lithium bis(amino)cyclodiphosph(III)azane, $[\text{Li}(\text{thf})(\text{tBuN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$, led to the formation of bicyclic silicon complex, $\text{cis}-[(\text{tBuN})\text{P}(\mu\text{-N}^t\text{Bu})]_2\text{SiCl}_2$. The germanium and tin analogs were found to be better synthesized by reacting the corresponding tetrachlorides with tin(II) bis(amino)cyclodiphosph(III)azane complexes, $\text{cis}-[(\text{tBuN})\text{P}(\mu\text{-N}^t\text{Bu})]_2\text{Sn}$.

Scheme 1.41. Reactions of dianionic cyclodiphosph(III)azanes with group 15 metal chlorides.^{109,110}

Moving across the periodic table, dianionic cyclodiphosph(III)azanes were also found to react with various group 15 chlorides to produce a series of bicyclic compounds

(Scheme 1.41).^{109,110} The bicyclic complexes formed in these reactions were structurally identical. Except for the bigger antimony(III) and bismuth(III) analogs, an additional intramolecular base stabilization from the endocyclic nitrogen of the P₂N₂ ring was observed. Nevertheless, the Cl substituents on the group 15 bicyclic complexes were replaced by X substituents in salt elimination reactions, to produce a variety of substituted complexes (Scheme 1.41).

1.6.3 – Biological uses of cyclodiphosph(III)azanes

Most cyclodiphosph(III)azanes are highly sensitive to air and moisture, rendering them unsuitable for biological application as they are likely to be unstable in physiological conditions. However, in the past decade, there were reports accounting on methods to improve the air and moisture stabilities of these cyclodiphosph(III)azanes. Among the accounts to enhance the air and moisture stability of cyclodiphosphazanes, there were a few reporting on the subsequent biological applications of the stabilized compounds. We will highlight three of such examples, shown in Fig. 1.16, reported by Balakrishna and co-workers on separate occasions.

Figure 1.16. Examples of cyclodiphosphazane compounds that are tested to have anti-cancer effect.^{50,52}

To make cyclodiphosph(III)azanes less sensitive to hydrolysis, the Balakrishna group performed methylation on the P₂N₂-based compound with the use of excess methyl iodide under reflux conditions. The methylation reaction performed on [(*t*BuHN)P(μ -N^{*t*Bu})]₂ (**1.3**) produced mono P-methylated product, *cis*-[{(*t*BuHN)P(μ -N^{*t*Bu})₂P(Me)(NH^{*t*Bu})}(I)]. The methylated cyclodiphosphazane was then further

reacted with $[\text{AuCl}(\text{SMe}_2)]$ to yield gold(I) complex, *cis*- $[\{(\text{tBuHN})\text{P}(\text{AuI})(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{Me})(\text{NH}^t\text{Bu})\}(\text{Cl})]$, which was tested and found to be anti-tumour active (*Fig. 1.16*). The antiproliferative result obtained showed that the gold(I) cyclodiphosphazane complex exhibited activity, comparable to the benchmark anticancer drug cisplatin, in HeLa cells.⁵⁰

On the other occasion, the team reported on antitumour active transition metal – copper(I) – complexes. Instead of the commonly used *tert*-butyl substituted bis(amino)cyclodiphosphazane, they synthesized pyridyl-incorporated cyclodiphosphazane, $[(\text{O-CH}_2\text{-2-C}_5\text{H}_4\text{N})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (**L**), and further complexation to copper(I) iodide resulted in 1D coordination polymer. Treatment of the coordination polymer with 2,2'-bipyridine (bpy) and 1,10-phenanthroline (phen) yielded two mixed-ligand copper(I) complexes. Both synthesized copper(I) complexes were tested for antiproliferative activity on HeLa cells and found to be more active as compared to cisplatin (% inhibition at 10 μM : 60 ± 2 and 97 ± 3 for $[\{\text{Cu}(\text{bpy})\}_2\text{L}]$ and $[\{\text{Cu}(\text{phen})\}_2\text{L}]$, respectively *cf.* 44 ± 7 (cisplatin)) (*Fig. 1.16*).

These and other reported results illustrate the promising application of cyclodiphosphazanes in biological arenas. This therefore prompts for continuous studies in the background for design of morefunctionalized cyclodiphosphazanes which can serve as pool of study candidates for improving the selectivity of these potential anti-tumour drugs.

1.7 - Bonding, geometry and conformation of cyclodiphosph(III)azanes

Among all the structurally characterized cyclodiphosph(III)azane ring systems, it has been observed that the endocyclic nitrogen atoms within the four-membered P_2N_2 ring exhibit sp^2 hybridised planar geometry, and the phosphorus atoms are sp^3 hybridised, pyramidal. In view of the hybridisation and geometry of the nitrogen and phosphorus

atoms, the cyclodiphosph(III)azane rings can adopt two different conformers: one in which the substituents on the phosphorus atoms are oriented in *cis* manner (same side of the P_2N_2 ring), while the other conformer has the substituents oriented in *trans* (opposite side of the P_2N_2 ring). The P_2N_2 ring in the *cis* isomers are normally found to be puckered, whereas that in the *trans* isomers tend to be planar.⁴⁰

Figure 1.17. Isomerization between *cis* and *trans* isomers of cyclodiphosph(III)azanes.⁴⁰

Theoretical calculations have shown that the *cis* conformation is usually more thermodynamically favoured, although the energy difference between the two isomers is relatively small ($4 - 40 \text{ kJ}\cdot\text{mol}^{-1}$) (Fig. 1.17).⁴⁰ Depending on the substituents on both the phosphorus and nitrogen atoms, the energy difference between the two isomers may be small enough for the compound to exist in both *cis* and *trans* conformations. Some general rules concerning the favourability of *cis* isomers formulated by Norman *et al.*,¹¹¹ and simplified by Stahl,⁴⁰ are summarized as follows:

- 2,4-Dihalocyclodiphosph(III)azanes, where phosphorus atoms bear halide substituents, are always *cis* regardless of the nitrogen substituent.
- 1,3-Diaryl-2,4-bis(amino)cyclodiphosph(III)azanes will be *cis* as long as at least one of the phosphorus substituents is a primary amine.
- 1,3-Dialkyl-2,4-bis(amino)cyclodiphosph(III)azanes are always *cis*.

Figure 1.18. Illustration of highest occupied molecular orbital (HOMO) of the naked P_2N_2 ring.

The P_2N_2 ring puckering observed in the *cis* conformation can be rationalized by molecular orbital (MO) theory and the steric strain attributed from the *cis* orientation of the substituents (Fig. 1.18). The highest occupied molecular orbital (HOMO) is essentially the π^* MO of the naked P_2N_2 ring. The ring puckering reduces the antibonding interactions and thus releases some degree of the inherent steric strain, by having the substituents arranged on the same side of the P_2N_2 ring, *i.e.* *cis*. The antibonding character of the HOMO can be influenced by the substituents attached on the phosphorus atoms. Electron-donating substituents, attached to the phosphorus atoms, increase the electron density around the phosphorus centers which can enhance the antibonding character of the HOMO, leading to an increase in ring puckering. Conversely, electron-withdrawing substituents reduce the antibonding character of the HOMO and resulting in a close-to-planar P_2N_2 ring that adopts the *trans* conformation, releasing the steric strain. It is important to note that this simplified model only takes into consideration the effects of the σ -donating or accepting substituents. For instance, when the phosphorus substituent is a π -donor such as phenylamine, the nitrogen lone pair is generally found to be orthogonal to the HOMO of the ring, therefore precluding any potential interaction between them, as seen in the solid-state structure of $[(PhHN)P(\mu-N^tBu)]_2$ (Fig. 1.19).^{40,112}

Figure 1.19. The orthogonal orientation of the nitrogen lone pair in $[(PhHN)P(\mu-N^tBu)]_2$.^{40,112}

The phosphorus(III)-nitrogen bond lengths within the P_2N_2 rings of cyclodiphosph(III)azanes are found to be 1.65 - 1.75 Å,^{40,112} which is shorter than the standard P-N single bond length (1.77 Å)¹¹³ found in phosphoramidate anion, $(NH_2PO_3H)^-$. Even shorter P-N bond lengths are observed within the P_2N_2 rings when

electronegative and σ -withdrawing chlorine substituents are attached to the phosphorus atoms, as compared to those attached with π -donating amine substituents. This suggests that an electron-deficiency at the phosphorus atoms has resulted in an increased strength of the P-N bonds. A few theories have been proposed to explain the apparent shortening of the P-N bonds within the P_2N_2 rings. The theories are summarized below:

- Ionic contribution to the P-N bond: The significant difference in electronegativity between nitrogen and phosphorus clearly leads to a substantial ionic contribution to the P-N bond. The presence of electron-withdrawing group will increase the electron-poor character of phosphorus, therefore increasing the ionic character in the bond even further.¹¹⁴
- $d\pi$ - $p\pi$ bonding: The degree of the participation of the d-orbitals of the phosphorus atoms is debated as the orbitals may be too high in energy to interact significantly in any π -bonding with the lone pair of nitrogen. It has been established that introducing an electron-withdrawing groups on the phosphorus can decrease the phosphorus electron density, thereby resulting in a contraction of the d-orbitals and lowering in their energy (*i.e.* so that they are able to interact more efficiently). *Ab initio* calculations on related P-N compounds suggest that the participation from the d-orbitals is probably insignificant.¹¹⁵
- Negative hyperconjugation between nitrogen lone pair and σ_{P-X}^* orbitals: The conformation in cyclodiphosph(III)azanes, in which the phosphorus and nitrogen lone pairs have a gauche relationship to reduce the repulsion between them, is expected to be favoured however it is not observed.¹¹⁶ Rather, the formation of the ring leads to a deviation from the expected orthogonal relationship between the lone pairs (*Fig. 1.20*).

Figure 1.20. Newman Projection showing the relationship between the phosphorus and nitrogen lone pairs in cyclodiphosph(III)azanes.

Ab initio and DFT calculations have been carried out on theoretical compounds $[\text{ClP}(\mu\text{-NMe})]_2$ and $[\text{ClP}(\mu\text{-NSiH}_3)]_2$, and have shown that negative hyperconjugation is significant in the P-N bond of cyclodiphosph(III)azanes.¹¹⁷ In addition, *ab initio* calculations performed on related species F_2PNH_2 have indicated that the negative hyperconjugation between the P-F σ^* orbital and the nitrogen lone pair is about one order of magnitude more important than $d\pi\text{-}p\pi$ bonding.¹¹⁸

1.8 - Aims

Cyclodiphosph(III)azanes are known to be highly susceptible towards air and moisture, hindering their potential utility in many areas. The syntheses of substituted cyclodiphosphazanes generally require strict exclusions of oxygen and moisture to minimize the possibility of oxidation and/or hydrolysis to undesired phosphorus(V) derivatives. In addition, the poor solubility of reactants of interest occasionally hinders the desired reactions from occurring. Hence, considering these issues, we aim to employ the use of mechanochemical ball milling as an alternative to address the solubility problems of reactants for the syntheses of functionalized cyclodiphosphazanes. On top of that, we intend to utilize mechanochemistry to generate air- and moisture-stable cyclodiphosphazanes in one-pot one-step manner. As there is a limited library of air- and moisture-stable cyclodiphosphazanes reported to date, detailed studies on the air- and hydrolytic-stabilities of synthesized cyclodiphosphazanes will be performed with the use of $^{31}\text{P}\text{-}\{^1\text{H}\}$ NMR spectroscopy (*Chapter 3*). Among the large volume of

cyclodiphosph(III)azanes known, the common moieties seen in the cyclodiphosphazanes are P-N, P-O, P-S and P-C moieties, formed by the nucleophilic substitution reaction of dichlorocyclodiphosphazanes. In this thesis, we aim to prepare and isolate a new class of cyclodiphosphazane-based compounds bearing P-OC(O) moiety and further study the reactivity of the moiety by conducting oxidation reactions on one of the macrocycles obtained (*Chapter 4*). It has been noticed that cyclodiphosphazanes generally lack manipulative functional groups, therefore preventing further functionalization and hence limits the exploration and development of other potential applications of these compounds. With these inadequacies identified, different cyclodiphosphazane-based frameworks, bearing protected functional groups, will be prepared and characterized for further studies on widening their applicability (*Chapter 5*). Lastly, we propose to fill up the gap between bis- and tetrakis- (cyclodiphosphazane) compounds by generating the tris- species with the use of trifunctional organic linker. In addition, we aim to exploit the trifunctional organic linker to design and synthesize a new and unique P₂N₂-based macromolecular compound (*Chapter 6*).

Henceforth, in the subsequent chapters of this thesis, the focus will be placed on cyclodiphosphazanes, with in depth analysis and discussion addressing the following areas, (i) alternative synthetic method for these compounds, (ii) novel cyclodiphosphazane-based compounds, (iii) enhancement of air and moisture-stability of these compounds and (iv) new developments for cyclodiphosphazanes.

Chapter 2 – General Experimental and Analytical Techniques

2.1 - General Procedures

In this thesis, the starting materials and compounds synthesized are potentially air- and moisture-sensitive. They are highly susceptible to oxidation and/or hydrolysis upon exposure to air and/or moisture. Meticulous precautions are required to prevent or minimize any contact of these materials with oxygen and water. Therefore, standard inert-atmosphere techniques are employed throughout the work described here. For projects involving air and hydrolytic stabilities studies, the synthesized compounds were first treated as air- and moisture-sensitive for all spectroscopic characterization and analyses.

2.1.1 - Inert-atmosphere techniques – Glovebox

Figure 2.1. Pictorial illustration of a glovebox.

An argon-filled glovebox ("Innovative Technology Inc", System One) was employed to isolate and store starting materials and synthesized compounds. Preparation of samples for analytical and spectroscopic characterizations were also carried out in the glovebox. A detailed figure of the glovebox is shown above. Posting ports were used to transport materials in and out of the glovebox. These ports must be evacuated and filled with argon to protect the established inert atmosphere of the box. Prior to transferring reagents and products into the glovebox, glasswares must be evacuated under vacuum before placing them into posting ports. A diaphragm pump constantly recirculates the

argon atmosphere through two columns. One of the columns consists of a copper catalyst that absorbs oxygen while the other one contains molecular sieves to remove moisture. A moisture and oxygen analyzer has been fitted to the box for monitoring of the atmosphere in the glovebox. Typical values for moisture is 0.54 ppm whereas for oxygen, it is 0.1-15 ppm. Reformation of the glovebox was conducted periodically to ensure the inert environment was maintained.

2.1.2 - Inert-atmosphere techniques – Schlenk Line and Schlenk Tubes

Figure 2.2. Pictorial illustration of a vacuum-line.

Argon from the cylinders was first dried *via* passing through drying column containing cobalt(II) chloride, followed by phosphorus pentoxide and molecular sieves before connecting to the Schlenk line. All the Schlenk tubes were evacuated 3 times and refilled with dry argon between evacuations prior to setting up of reactions. This procedure is essential to ensure an anaerobic atmosphere is established and kept. All solvents and liquid reagents are transferred *via* dry syringes into Schlenk tubes which are prepared beforehand. All solid reagents are weighed in glovebox, transferred into Schlenk tubes and brought out for reactions.

2.1.3 – Inert-atmosphere techniques – Mechanochemical Synthetic Methods

Mechanochemical ball milling technique was employed as greener synthetic alternative in this thesis. All the mechanochemical reactions were conducted in 10 mL stainless

steel milling jars and were prepared in an argon-filled glovebox due to the intrinsic air and moisture-sensitivities of the starting materials.

Figure 2.1. Stainless steel milling jars and 10 mm stainless steel ball.

These jars were loaded with the reaction mixtures along with 10 mm stainless steel ball (4.0153 g). These filled jars were then brought out of the glovebox and milled at 30 Hz on Retsch Mixer Mill MM400 machines. The mechanical force generated can be adjusted by modifying the frequency and duration of milling. All manipulations to purify and isolate crystalline compounds were then carried out using Schlenk techniques and glovebox under inert atmosphere.

2.1.4 - Nuclear Magnetic Resonance (NMR) Spectroscopy

Spectroscopic-grade deuterated NMR solvent (CDCl_3) was distilled over CaH_2 and stored under $4\text{\AA}$ molecular sieves under argon prior to use. For deuterated benzene (C_6D_6), sodium wire was added to a round-bottomed flask (RBF) of C_6D_6 and distilled, then stored under argon with $4\text{\AA}$ molecular sieves. Other deuterated solvents were used as received, unless otherwise stated. Samples were prepared by taking about 20 mg of the compounds and placed into thin-walled NMR tubes (Wilmad, 535-LPV-7). The samples in the NMR tubes were taken out from the glovebox and connected to Schlenk line and filled with argon while pre-dried deuterated solvent, under argon, was drawn by dry syringe and added into the NMR tubes to dissolve the samples. NMR spectra were recorded at the following frequencies: 400 MHz (^1H), 101 MHz (^{13}C), 162 MHz (^{31}P) using Bruker AvanceIII 400 (BBFO probe) and Bruker Avance 400 (QNP probe)

spectrometers. ^1H and ^{13}C NMR spectra were recorded in dried CDCl_3 or C_6D_6 as an internal standard. ^{31}P NMR spectra were referenced to 85% $\text{H}_3\text{PO}_4/\text{D}_2\text{O}$ as the external standard. ^{13}C and ^{31}P NMR spectra were acquired using broad band decoupling. For ^1H NMR spectroscopy, spectra were internally referenced to signal at a singlet at δ 7.26 or 7.16 ppm for CDCl_3 and C_6D_6 , respectively. For ^{13}C NMR spectroscopy, a triplet at δ 77.16 or 128.06 ppm for CDCl_3 and C_6D_6 , respectively. All reactions are monitored *via in situ* $^{31}\text{P}\{^1\text{H}\}$ NMR (*ex situ* for mechanochemical reactions). The *in situ* NMR was carried out by drawing about 0.4 mL of reaction solution into a NMR tube and recorded immediately.

2.1.5 - Single Crystal X-ray Diffraction Studies

X-ray crystallography was the principal tool for solid-state structure determination. The crystal structure machines used are Bruker X8 CCD Diffractometer and Bruker Kappa CCD Diffractometer. They were equipped with CCD detectors. Depending on the size of the single crystals, either Cu ($\lambda = 1.54178 \text{ \AA}$) or Mo ($\lambda = 0.71073 \text{ \AA}$) K α radiation was used with the APEX2 suite of programs.¹¹⁹ For all the compounds reported in this report, the crystals were grown from saturated solution in Schlenk tubes under argon in various temperature (room temperature: +25 °C; refrigerator temperature: +5 °C; and freezer temperature: -22 °C). The ‘oil drop mounting technique’ was used to extract crystals from Schlenk tubes using a spatula and immediately coat them in inert perfluorinated polyether oil (Fomblin® Y). The oil-coated crystals were examined under microscope and a suitable single crystal was then selected and mounted onto a small glass fibre attached to the diffractometer goniometer head. Once the fibre was attached, a cooled dry nitrogen gas stream was applied to freeze the oil coated around the crystal and hence fixing the orientation of the crystal and preventing oxidation and hydrolysis. The reflections were recorded and processed with Bruker SAINT software

package which uses narrow-frame algorithm. The structures were solved *via* direct methods with the SHELXTL software package and refined by full-matrix least-squares calculations on F^2 with anisotropic displacements parameters assigned to all atoms.¹²⁰ For crystals that are twinned, using the program CELL_NOW,¹²¹ the twin law and cell parameters were determined. The reflection data were then processed and corrections were consolidated using the program TWINABS.¹²²

2.1.6 - Infra-red (IR) Spectroscopy

All air- and water-sensitive samples were prepared in the glovebox with the appropriate tools (NaCl plates, mortar and Nujol oil). For air- and water-stable compounds, the samples were prepared in room temperature and atmosphere. A Nujol mull of the compounds was smeared between two sodium chloride windows ($4000 - 500\text{ cm}^{-1}$). The windows were kept into a box of silica gel to minimize the chance of oxidation and hydrolysis by atmosphere and transferred out of the glovebox. The samples were immediately transferred to the spectrometer (Shimadzu IRPrestige-21 FTIR).

2.1.7 - Elemental Analysis

Elemental analyses were performed using Euro Vector Euro EA Elemental Analyzer (CHNS). For air- and moisture-sensitive samples, the tools used for sample preparation were brought into the argon-filled glovebox and the samples were prepared inside the glovebox. As for stable samples, the preparation was carried out in normal atmosphere. Prior to the analysis, samples of standard (2,5-bis(5-*tert*-butyl-2-benzo-oxazol-2-yl) thiophene (BBOT)) were prepared and ran to obtain an acceptable calibration curve.

2.1.8 - Mass Spectrometry

High-resolution ESI mass spectra were obtained using a Waters Q-Tof Premier. Solvents used to prepare the sample were distilled to remove any moisture and stored

under 4 Å molecular sieves prior to use. All the compounds synthesized are stable enough to tolerate the traces of moisture present during the analysis.

2.1.9 - Melting Point Determination

The preparation of samples was done in the glovebox. Samples were packed into melting point capillary tubes to about 0.5 cm in height. The tubes must be sealed with silicon grease to minimize oxidation and hydrolysis. Melting points of the samples was measured using standard melting point apparatus (Optimelt MPA100 Automated Melting Point System). Melting points reported were uncorrected.

2.2 - Preparation of Starting Materials

All solvents were purified by standard procedures - distilled and stored in Schlenk storage tubes with 4Å molecular sieves under argon prior to use.¹²³ Toluene, tetrahydrofuran (THF), *n*-hexane, diethyl ether (Et₂O) and *n*-pentane were freshly distilled over Sodium/Benzophenone and stored with molecular sieves under argon. Starting materials used in the reactions performed were either commercially available and used without further purification or synthesized as described below. Phosphorus trichloride was distilled to remove traces of oxidized derivative (Cl₃P=O) and stored over 4Å molecular sieves under argon. *tert*-butylamine and triethylamine were distilled over potassium hydroxide and stored over 4Å molecular sieves under argon.

2.2.1 - Synthesis of [ClP(μ-*N*^tBu)]₂ (**1.1**)³¹

Compound **1.1** was prepared from modified synthetic procedure.³¹ To a 3-neck round-bottomed flask fitted with a 250 mL dropping funnel, phosphorus trichloride (17.5 cm³,

200.0 mmol) was added into 300 mL of THF into the RBF. *Tert*-butylamine (21.0 cm³, 200.0 mmol) and triethylamine (56.0 cm³, 400.0 mmol) were loaded into the dropping funnel and added dropwise into the RBF at -78 °C over a period of 2.0 hours. The reaction mixture was left to stir overnight. The resulting ammonium salt was filtered off over a frit consisting Celite (P3). The filtrate was evaporated under reduced pressure till no more solvent left and then vacuum distilled to obtain crystalline solid of **1.1** (96 °C, under vacuum (0.2 mmHg)) Average yield: 63 % (17.3 g, 63.0 mmol). ¹H NMR (C₆D₆, 400 MHz): δ 1.18 (s); ³¹P{¹H} NMR (C₆D₆, 162 MHz): δ 207.01 (s);

2.2.2 - Synthesis of [(^tBuHN)P(μ-^tBu)₂PCl] (**1.2**)¹²⁴

Compound **1.2** was prepared according to the reported synthetic procedure.¹²⁴ To a 3-neck round-bottomed flask fitted with a 250 mL dropping funnel, phosphorus trichloride (20.0 cm³, 229.2 mmol) was added into 300 mL of THF into the RBF. *Tert*-butylamine (96.0 cm³, 913.5 mmol) in 100 mL THF was loaded into the dropping funnel and added dropwise into the RBF at -78 °C over a period of 2.0 hours. The reaction mixture was left to stir overnight and the ammonium salt was filtered off over a frit consisting Celite (P3). The solvent was evaporated under reduced pressure and residue was recrystallized in hexane at -20 °C to obtain colorless crystals.

2.3 - Syntheses of new compounds in Chapter 3

2.3.1 - Synthesis of [(AdO)P(μ -N^tBu)]₂ (3.1)

A mixture of **1.1** (0.233 g, 0.85 mmol), 1-adamantanol (0.258 g, 1.7 mmol) and triethylamine (0.24 cm³, 1.7 mmol) were loaded into the 10 mL milling jar with a 10 mm ball in the glovebox. The reaction was milled for 3.5 hours at 30 Hz. Hexane was added to extract product and triethylammonium chloride was filtered off. The resulting filtrate was concentrated to yield off-white solid. Solid was isolated and dried under vacuum to give spectroscopically pure product. Yield: 0.430 g (59 %); ¹H NMR (CDCl₃, 400 MHz): δ 2.12 (br s, 6H, CH), 2.08 (br s, 12H, C(CH₂)₃), 1.62 (br s, 12H, CH₂), 1.35 (s, 18H, C(CH₃)₃); ¹³C NMR (C₆D₆, 101 MHz): δ 77.12 (s, O-C), 52.41 (t, ²J_{P-C} = 12.6 Hz, C(CH₃)₃), 44.34 (t, ³J_{P-C} = 4.0 Hz, O-C-CH₂), 36.59 (s, CH₂), 31.98 (t, ³J_{P-C} = 7.1 Hz, C(CH₃)₃), 31.57 (s, O-C-CH₂-CH); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 128.27 (s); m.p. 168 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1067 (C-O); MS (EI) *m/z*: 507.32 [M+1]⁺;

2.3.2 - Synthesis of [(AdHN)P(μ -N^tBu)]₂ (3.2)

Identical to synthetic procedure for **3.1**, **1.1** (0.324 g, 1.2 mmol), 1-adamantanamine (0.356 g, 2.4 mmol) and triethylamine (0.33 cm³, 2.4 mmol) were used. The reaction

was milled for 3.5 hours at 30 Hz and transferred into Schlenk tube. THF was added to extract product and triethylammonium chloride was filtered off. The resulting filtrate was concentrated to yield white pure solid. Yield: 0.091 g (15 %); ^1H NMR (CDCl_3 , 400 MHz): δ 2.53 (d, $^2J_{\text{P-H}} = 7.2$ Hz, 2H, N-**H**), 2.03 (s, 6H, **CH**), 1.84 (s, 12H, C(**CH**₂)₃), 1.63 (t, $^3J_{\text{H-H}} = 2.8$ Hz, 12H, **CH**₂), 1.30 (s, 18H, C(**CH**₃)₃); ^{13}C NMR (CDCl_3 , 101 MHz): δ 52.13 (q, $^2J_{\text{P-C}} = 11.0$ Hz, C(**CH**₃)₃), 52.05 (s, N-C), 47.19 (d, $^3J_{\text{P-C}} = 10.1$ Hz, N-C-**CH**₂), 36.63 (s, **CH**₂), 31.89 (t, $^3J_{\text{P-C}} = 7.1$ Hz, C(**CH**₃)₃), 30.16 (s, N-C-CH₂-**CH**); ^{31}P - $\{^1\text{H}\}$ NMR (CDCl_3 , 162 MHz): δ 89.2 (s); m.p. 202 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 3333 (N-H); MS (EI) m/z : 505.36 [$\text{M}+1$]⁺;

2.3.3 - Synthesis of [(*p*-NHC₆H₄CN)P(μ -N^{*t*}Bu)]₂ (3.3)

Identical to synthetic procedure for **3.1**, **1.1** (0.230 g, 0.84 mmol), 4-aminobenzonitrile (0.198 g, 1.7 mmol) and triethylamine (0.24 cm³, 1.7 mmol) were used. The reaction was milled for 3.0 hours at 30 Hz and transferred into Schlenk tube. THF was added to extract product and triethylammonium chloride was filtered off. The resulting filtrate was concentrated to yield white solid which was further washed with cold THF. Yield: 0.177 g (48 %); ^1H NMR (CDCl_3 , 400 MHz): δ 7.47 (d, $^3J_{\text{H-H}} = 8.4$ Hz, 4H, *m*-Ar**H**), 7.10 (d, $^3J_{\text{H-H}} = 8.4$ Hz, 4H, *o*-Ar**H**), 5.71 (s, 2H, N**H**), 1.25 (s, 18H, C(**CH**₃)₃); ^{13}C NMR (CDCl_3 , 101 MHz): δ 150.46 (s, N-Ar**C**), 133.80 (s, *m*-Ar**C**), 116.63 (d, $^3J_{\text{P-C}} = 14.0$ Hz, *o*-Ar**C**), 114.59 (s, C $\equiv$ N), 102.60 (s, Ar**C**-CN), 52.76 (d, $^3J_{\text{P-C}} = 8.0$ Hz, C(**CH**₃)₃), 31.13 (t, $^3J_{\text{P-C}} = 6.2$ Hz, C(**CH**₃)₃); ^{31}P - $\{^1\text{H}\}$ NMR (CDCl_3 , 162 MHz): δ 105.82 (s); m.p. 182-

183 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 3173 (N-H), 2212 (C≡N), 1601 (NH bending); MS (EI) m/z : 439.19 [M+1]⁺;

2.3.4 - Synthesis of [(MesHN)P(μ -N^tBu)]₂ (3.4)

Identical to synthetic procedure for **3.1**, **1.1** (0.550 g, 2.0 mmol), mestylamine (0.56 cm³, 4.0 mmol) and triethylamine (0.56 cm³, 4.0 mmol) were used. The reaction was milled for 4.0 hours at 30 Hz and transferred into Schlenk tube. Toluene was added to extract product and triethylammonium chloride was filtered off. The resulting filtrate was concentrated to yield colorless crystals. Yield: 0.416 g (44 %); ¹H NMR (C₆D₆, 400 MHz): δ 6.85 (s, 4H, *m*-ArH), 4.52 (s, 2H, N-H), 2.47 (s, 12H, *o*-ArCH₃), 2.18 (s, 6H, *p*-ArCH₃), 1.26 (s, 18H, C(CH₃)₃); ¹³C NMR (C₆D₆, 101 MHz): δ 137.24 (s, N-ArC), 131.44 (s, *p*-ArC), 130.03 (s, *o*-ArC), 129.49 (s, *m*-ArC), 51.42 (t, ²J_{P-C} = 14.6 Hz, C(CH₃)₃), 31.33 (t, ³J_{P-C} = 6.6 Hz, C(CH₃)₃), 20.80 (s, *p*-CH₃), 20.55 (t, ⁴J_{P-C} = 5.1 Hz, *o*-CH₃); ³¹P-{¹H} NMR (C₆D₆, 162 MHz): δ 111.30 (s); m.p. 151-153 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 3323 (N-H); MS (EI) m/z : 473.30 [M+1]⁺;

Table 2.2. Crystal data and structure refinement for compound **3.4**.

Empirical Formula	C ₂₆ H ₄₂ N ₄ P ₂	Volume (Å ³)	1355.1(3)
F _w	472.57 g/mol	Z	2
T (K)	103(2)	ρ_{calc} (g/cm ³)	1.158
λ (Å)	0.71073	μ , (mm ⁻¹)	0.181
Crystal System	Triclinic	F(000)	512
Space Group	P -1	Crystal Size (mm)	0.280 x 0.340 x 0.420
Cell length (Å)	a = 9.8798(12)	2 θ range (°)	1.51 to 31.18

	b = 10.1868(14)	Reflections collected	27066
	c = 14.441(2)	Indep. Refl. (R _{int})	8695 [R(int) = 0.0405]
Cell angles (°)	α = 107.017(4)	Larg. Diff. Peak & hole (eÅ ⁻³)	0.648 and -0.600
	β = 101.653(3)	R1, wR2 (I>2σ(I))	0.0455, 0.1121
	γ = 91.661(3)	R1, wR2 (all data)	0.0693, 0.1289

2.3.5 - Synthesis of [P(μ-N'Bu)]₂(μ-NH(C₅N₄H₂)) (3.5)

Identical to synthetic procedure for **3.1**, **1.1** (0.275 g, 1.0 mmol), adenine (0.270 g, 2.0 mmol) and triethylamine (0.28 cm³, 2.0 mmol) were used. The reaction was milled for 4.0 hours at 30 Hz and transferred into Schlenk tube. THF was added to the mixture and filtered to remove triethylammonium chloride. The filtrate was left at room temperature to yield colorless crystals. Yield: 0.272 g (81 % based on **1.1**); ¹H NMR (CDCl₃, 400 MHz): δ 8.78 (s, 1H, *P*-N-CH), 8.38 (s, 1H, CH), 7.19 (s, 1H, N-H), 1.04 (s, 18H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 164.38 (s, ArC), 153.42 (s, ArCH), 157.12 (d, ²J_{P-C} = 10.1 Hz, ArCH), 148.06 (d, ²J_{P-C} = 22.2 Hz, NH-ArC), 117.19 (s, ArC), 52.32 (t, ²J_{P-C} = 7.1 Hz, C(CH₃)₃), 30.18 (t, ³J_{P-C} = 6.1 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 155.22 (d, ²J_{P-P} = 21.1 Hz, *P*-N), 150.27 (d, ²J_{P-P} = 21.1 Hz, *P*-NH); m.p. 222 °C; MS (EI) *m/z*: 338.14 [M+1]⁺;

Table 2.3. Crystal data and structure refinement for compound **3.5**.

Empirical Formula	C ₁₀₀ H ₁₆₀ N ₅₂ O ₃ P ₁₂₀	Volume (Å ³)	3172.7(3)
F _w	2510.43 g/mol	Z	1
T (K)	100(2)	ρ _{calc} (g/cm ³)	1.314

λ (Å)	0.71073	μ , (mm ⁻¹)	0.230
Crystal System	Triclinic	F(000)	1328
Space Group	P -1	Crystal Size (mm)	0.200 x 0.240 x 0.300
Cell length (Å)	a = 13.7327(9)	2 θ range (°)	2.28 to 30.11
	b = 15.0009(9)	Reflections collected	173955
	c = 15.7353(9)	Indep. Refl. (R _{int})	18585 [R(int) = 0.1173]
Cell angles (°)	α = 98.868(2)	Larg. Diff. Peak & hole (eÅ ⁻³)	1.409 and -0.679
	β = 95.840(2)	R1, wR2 (<i>I</i> > 2 σ (<i>I</i>))	0.0687, 0.1658
	γ = 94.264(2)	R1, wR2 (all data)	0.1166, 0.2049

2.3.6 - Synthesis of [(AdO)(S)P(μ -N^tBu)]₂ (**3.6**)

A mixture of **1.1** (0.275 g, 1.0 mmol), 1-adamantanol (0.304 g, 2.0 mmol) and elemental sulfur (0.096 g, 3.0 mmol) were added into a mechanochemical grinder reaction vessel along with triethylamine (0.28 cm³, 2.0 mmol) and 10 mm stainless steel ball. The reaction was milled for 7.0 hours at 30 Hz. Toluene was added to extract product and, triethylammonium chloride and unreacted sulfur were filtered off. The solution was concentrated and left to crystallize at room temperature. Yield: 0.204 g (31 %); ¹H NMR (CDCl₃, 400 MHz): δ 2.31 (d, ⁴J_{P-H} = 2.4 Hz, 12H, OC(**CH**₂)₃), 2.20 (s, 6H, **CH**), 1.65 (s, 12H, CH**CH**₂), 1.63 (s, 18H, C(**CH**₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 87.96 (d, ²J_{P-C} = 7.1 Hz, O-**C**), 57.44 (s, **C**(CH₃)₃), 44.00 (s, O-C-**CH**₂), 36.00 (s, **CH**₂), 31.66 (s, O-C-**CH**₂-**CH**), 30.32 (t, ³J_{P-C} = 5.1 Hz, C(**CH**₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 39.52 (s); m.p. 241-242 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1051 (C-O), 988 (P-OC),

910 (P-OR), 760 (P=S); MS (EI) m/z : 571.27 $[M+1]^+$; Anal. Calcd for $C_{28}H_{50}N_2O_3P_2S_2$: C, 57.12; H, 8.56; N, 4.76; S, 10.89. Found: C, 57.47; H, 8.12; N, 8.12; S, 10.84 %

Table 2.4. Crystal data and structure refinement for compound **3.6**.

Empirical Formula	$C_{28}H_{48}N_2O_2P_2S_2$	Volume ($\text{\AA}^3$)	2880.2(3)
F_w	570.74 g/mol	Z	4
T (K)	153(2)	ρ_{calc} (g/cm ³)	1.316
λ ($\text{\AA}$)	0.71073	μ , (mm ⁻¹)	0.325
Crystal System	Monoclinic	F(000)	1232
Space Group	P 1 21/n 1	Crystal Size (mm)	0.180 x 0.220 x 0.420
Cell length ($\text{\AA}$)	$a = 15.8615(11)$	2θ range ($^\circ$)	1.45 to 28.85
	$b = 6.9081(5)$	Reflections collected	29542
	$c = 26.3622(17)$	Indep. Refl. (R_{int})	7507 [$R(\text{int}) = 0.0900$]
Cell angles ($^\circ$)	$\alpha = 90$	Larg. Diff. Peak & hole ($e\text{\AA}^{-3}$)	0.681 and -0.436
	$\beta = 94.360(2)$	R1, wR2 ($I > 2\sigma(I)$)	0.0478, 0.1160
	$\gamma = 90$	R1, wR2 (all data)	0.0620, 0.1263

2.3.7 - Synthesis of $[(\text{AdO})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (**3.7**)

Identical to the procedure for synthesis of **3.6**, **1.1** (0.275 g, 1.0 mmol), 1-adamantanol (0.304 g, 2.0 mmol) and elemental selenium (0.237 g, 3.0 mmol) along with triethylamine (0.28 cm³, 2.0 mmol) were used. The reaction was milled for 6.0 hours at 30 Hz. Toluene was added to extract product and, triethylammonium chloride and unreacted selenium were filtered off. The solution was concentrated and left to stand at room temperature to obtain colorless crystals. Yield: 0.352 g (62 %); ¹H NMR (CDCl_3 , 400 MHz): δ 2.35 (s, 12H, $\text{OC}(\text{CH}_2)_3$), 2.21 (s, 6H, CH), 1.70 (s, 12H, CH_2), 1.65 (s,

18H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 89.89 (d, ²J_{P-C} = 15.2 Hz, PO-C), 58.35 (s, OC(CH₂)₃), 44.01 (t, ²J_{P-C} = 2.0 Hz, C(CH₃)₃), 35.93 (s, CH₂), 31.73 (s, CH), 30.46 (t, ³J_{P-C} = 4.5 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 24.62 (s, ¹J_{P-Se} = 930.4 Hz); m.p. 198-200 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1011 (P-OC), 897 (P=Se); MS (EI) *m/z*: 665.16 [M-1]⁺; Anal. Calcd for C₂₈H₄₈N₂O₂P₂Se₂: C, 50.61; H, 7.28; N, 4.22. Found: C, 50.82; H, 7.74; N, 4.49 %.

Table 2.5. Crystal data and structure refinement for compound **3.7**.

Empirical Formula	C ₂₈ H ₄₈ N ₂ O ₂ P ₂ Se ₂	Volume (Å ³)	1495.5(2)
F _w	664.54 g/mol	Z	2
T (K)	153(2)	ρ _{calc} (g/cm ³)	1.476
λ (Å)	0.71073	μ, (mm ⁻¹)	2.607
Crystal System	Monoclinic	F(000)	688
Space Group	P 1 21/m 1	Crystal Size (mm)	0.220 x 0.300 x 0.320
Cell length (Å)	a = 10.7455(9)	2θ range (°)	1.59 to 29.00
	b = 10.8723(9)	Reflections collected	21674
	c = 13.5836(12)	Indep. Refl. (R _{int})	4140 [R(int) = 0.1484]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	1.565 and -1.848
	β = 109.542(2)	R1, wR2 (I>2σ(I))	0.0924, 0.2277
	γ = 90	R1, wR2 (all data)	0.1358, 0.2428

2.3.8 - Synthesis of [(AdHN)(S)P(μ-N^tBu)]₂ (**3.8**)

Identical to the procedure for synthesis of **3.6**, **1.1** (0.550 g, 2.0 mmol), 1-adamantamine (0.604 g, 4.0 mmol) and elemental sulfur (0.192 g, 6.0 mmol) along with triethylamine

(0.56 cm³, 4.0 mmol) were used. The reaction was milled for 9.0 hours at 30 Hz. THF was added to extract product and, triethylammonium chloride and unreacted sulfur were filtered off. The filtrate was concentrated and equivolume of toluene was added. The resulting solution was left to crystallize at room temperature to give colorless crystals. Yield: 0.532 g (47 %); ¹H NMR (CDCl₃, 400 MHz): δ 2.97 (s, 2H, N-**H**), 2.09 (s, 18H, **CH** and **CH**₂), 1.69 (s, 18H, C(**CH**₃)₃), 1.67 (br s, 12H, **CH**₂); ¹³C NMR (CDCl₃, 101 MHz): δ 57.80 (s, N-**C**), 55.65 (t, ²J_{P-C} = 2.0 Hz, C(**CH**₃)₃), 44.79 (s, C(**CH**₂)₃), 36.31 (s, **CH**₂), 30.37 (t, ³J_{P-C} = 4.5 Hz, C(**CH**₃)₃), 30.06 (s, **CH**); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 38.53 (s); m.p. 258-259 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 3379 (N-H), 758 (P=S); MS (EI) *m/z*: 568.30 [M+1]⁺; Satisfactory C, H and N analysis could not be obtained.^{85,125}

Table 2.6. Crystal data and structure refinement for compound **3.8**.

Empirical Formula	C ₆₄ H ₁₁₂ N ₈ O ₂ P ₄ S ₄	Volume (Å ³)	6805.0(3)
F _w	1277.73 g/mol	Z	4
T (K)	100(2)	ρ _{calc} (g/cm ³)	1.247
λ (Å)	0.71073	μ, (mm ⁻¹)	0.282
Crystal System	Orthorhombic	F(000)	2768
Space Group	P n a 21	Crystal Size (mm)	0.100 x 0.140 x 0.220
Cell length (Å)	a = 24.3568(6)	2θ range (°)	2.65 to 27.00
	b = 9.8974(2)	Reflections collected	53479
	c = 28.2283(6)	Indep. Refl. (R _{int})	14773 [R(int) = 0.0449]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	1.964 and -0.659
	β = 90	R1, wR2 (<i>I</i> >2σ(<i>I</i>))	0.0597, 0.1503
	γ = 90	R1, wR2 (all data)	0.0642, 0.1543

2.3.9 - Synthesis of [(AdHN)(Se)P(μ -N^tBu)]₂ (3.9)

Identical to the procedure for synthesis of **3.6**, **1.1** (0.550 g, 2.0 mmol), 1-adamantamine (0.604 g, 4.0 mmol) and elemental selenium (0.474 g, 6.0 mmol) along with triethylamine (0.56 cm³, 4.0 mmol) were used. The reaction was milled for 10.0 hours at 30 Hz. THF was added to extract product and, triethylammonium chloride and unreacted selenium were filtered off. The filtrate was concentrated, and equal volume of toluene was added. The resulting solution was left to crystallize at room temperature to give colorless crystals. Yield: 0.562 g (42 %); ¹H NMR (CDCl₃, 400 MHz): δ 3.29 (s, 2H, N-**H**), 2.11 (s, 18H, **CH** and **CH**₂), 1.76 (s, 18H, C(**CH**₃)₃), 1.67 (s, 12H, **CH**₂); ¹³C NMR (CDCl₃, 101 MHz): δ 58.75 (s, N-**C**), 56.76 (t, ²J_{P-C} = 3.5 Hz, C(**CH**₃)₃), 44.75 (s, C(**CH**₂)₃), 36.26 (s, **CH**₂), 30.45 (t, ³J_{P-C} = 4.5 Hz, C(**CH**₃)₃), 30.05 (s, **CH**); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 23.45 (s, ¹J_{P-Se} = 873.2 Hz, ²J_{P-P} = 25.9 Hz); m.p. 256 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 3366 (N-H), 899 (P=Se); MS (EI) *m/z*: 663.20 [M+1]⁺; Anal. Calcd for C₂₈H₅₀N₄P₂Se₂: C, 50.76; H, 7.61; N, 8.46. Found: C, 51.07; H, 8.11; N, 8.11 %.

Table 2.7. Crystal data and structure refinement for compound **3.9**.

Empirical Formula	C ₂₈ H ₅₀ N ₄ P ₂ Se ₂	Volume (Å ³)	2960.58(17)
F _w	662.58 g/mol	Z	4
T (K)	103(2)	ρ _{calc} (g/cm ³)	1.487
λ (Å)	0.71073	μ, (mm ⁻¹)	2.631
Crystal System	Monoclinic	F(000)	1376
Space Group	P 1 21/n 1	Crystal Size (mm)	0.040 x 0.120 x 0.320

Cell length (Å)	a = 16.0802(6)	2θ range (°)	1.44 to 31.11
	b = 7.0317(2)	Reflections collected	40803
	c = 26.2586(9)	Indep. Refl. (R _{int})	9501 [R(int) = 0.0718]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (e ⁺ Å ⁻³)	0.0562 and -0.471
	β = 94.340(2)	R1, wR2 (I > 2σ(I))	0.0388, 0.0706
	γ = 90	R1, wR2 (all data)	0.0701, 0.0790

2.3.10 - Synthesis of [(*p*-NHC₆H₄CN)(*S*)P(*μ*-N^{*t*}Bu)]₂ (**3.10**)

Identical to the procedure for synthesis of **3.6**, **1.1** (0.275 g, 1.0 mmol), *p*-aminobenzonitrile (0.236 g, 2.0 mmol) and elemental sulfur (0.096 g, 3.0 mmol) along with triethylamine (0.28 cm³, 2.0 mmol) were used. The reaction was milled for 6.0 hours at 30 Hz. THF was added to extract product and, triethylammonium chloride and unreacted sulfur were filtered off. The filtrate was then concentrated and left to crystallize at room temperature. Yield: 0.203 g (40 %); ¹H NMR (CDCl₃, 400 MHz): δ 11.10 (br s, *HN*(CH₂CH₃)₃Cl), 7.66 (d, ³J_{H-H} = 8.4 Hz, 4H, *m*-Ar*H*), 7.53 (d, ³J_{H-H} = 8.4 Hz, 4H, *o*-Ar*H*), 3.77-3.73 (m, 2H, OCH₂ of THF), 3.11-3.04 (m, 6H, HN(CH₂CH₃)₃Cl), 1.85 (m, 2H, CH₂ of THF), 1.60 (s, 18H, C(CH₃)₃), 1.38 (t, ³J_{H-H} = 7.4 Hz, 9H, HN(CH₂CH₃)₃Cl); ¹³C NMR (CDCl₃, 101 MHz): δ 145.02 (s, N-ArC), 133.04 (s, *m*-ArC), 121.13 (t, ³J_{P-C} = 3.0 Hz, *o*-ArC), 119.26 (s, C≡N), 106.00 (s, ArC-CN), 57.04 (s, C(CH₃)₃), 46.45 (s, NH(CH₂CH₃)₃Cl), 29.94 (t, ³J_{P-C} = 4.5 Hz, C(CH₃)₃), 8.83 (s, NH(CH₂CH₃)₃Cl); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 39.43 (s); m.p. 272 °C; IR (mineral oil, NaCl) ν (cm⁻¹): IR (mineral oil, NaCl) ν (cm⁻¹): 3235 (N-H), 2220 (C≡N),

1601 (N-H bending), 1508 (aromatic C=C); MS (EI) m/z : 503.14 $[M+1]^+$; Satisfactory C, H and N analysis could not be obtained.^{73,85,125,126}

Table 2.8. Crystal data and structure refinement for compound **3.10**.

Empirical Formula	C ₃₂ H ₅₂ C/N ₇ OP ₂ S ₂	Volume (Å ³)	1903.1(2)
F _w	712.31 g/mol	Z	2
T (K)	153(2)	ρ _{calc} (g/cm ³)	1.243
λ (Å)	0.71073	μ, (mm ⁻¹)	0.329
Crystal System	Triclinic	F(000)	760
Space Group	P -1	Crystal Size (mm)	0.120 x 0.160 x 0.320
Cell length (Å)	a = 9.1079(7)	2θ range (°)	1.93 to 28.07
	b = 11.4296(8)	Reflections collected	31949
	c = 19.8336(15)	Indep. Refl. (R _{int})	9229 [R(int) = 0.0585]
Cell angles (°)	α = 75.8067(18)	Larg. Diff. Peak & hole (eÅ ⁻³)	0.371 and -0.441
	β = 87.554(2)	R1, wR2 (<i>I</i> > 2σ(<i>I</i>))	0.0452, 0.1063
	γ = 72.0615(19)	R1, wR2 (all data)	0.0684, 0.1191

2.3.11 - Synthesis of [(*p*-NHC₆H₄CN)(Se)P(*μ*-N^{*t*}Bu)]₂ (**3.11**)

Identical to the procedure for synthesis of **3.6**, **1.1** (0.275 g, 1.0 mmol), *p*-aminobenzonitrile (0.236 g, 2.0 mmol) and elemental selenium (0.237 g, 3.0 mmol) along with triethylamine (0.28 cm³, 2.0 mmol) were used. The reaction was milled for 6.0 hours at 30 Hz. THF was added to extract product and, triethylammonium chloride and unreacted selenium were filtered off. The THF filtrate was evaporated to dryness, and the product was recrystallized from methanol at room temperature. Yield: 0.388 g (65 %); ¹H NMR (MeOD, 400 MHz): δ 7.65 (dd, ³J_{H-H} = 8.8 Hz, ⁴J_{P-H} = 14.0 Hz, 8H,

ArH), 1.62 (s, 18H, C(CH₃)₃); ¹³C NMR (MeOD, 101 MHz): δ 145.90 (s, N-ArC), 134.04 (s, *m*-ArC), 122.88 (s, *o*-ArC), 119.89 (s, C≡N), 107.26 (s, ArC-CN), 58.59 (s, C(CH₃)₃), 30.35 (t, ³J_{P-C} = 4.5 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 30.09 (s, ¹J_{P-Se} = 909.4 Hz, ²J_{P-P} = 20.1 Hz); m.p. 232-233 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 3287 (N-H), 2224 (C≡N), 1603 (N-H bending), 1508 (aromatic C=C), 897 (P=Se); MS (EI) *m/z*: 599.03 [M+1]⁺; Satisfactory C, H and N analysis could not be obtained.^{73,85,125,126}

Table 2.9. Crystal data and structure refinement for compound **3.11**.

Empirical Formula	C ₂₄ H ₃₆ N ₆ O ₂ P ₂ Se ₂	Volume (Å ³)	2968.89(14)
F _w	660.45 g/mol	Z	4
T (K)	100(2)	ρ _{calc} (g/cm ³)	1.478
λ (Å)	0.71073	μ, (mm ⁻¹)	2.630
Crystal System	Orthorhombic	F(000)	1344
Space Group	P c a 21	Crystal Size (mm)	0.080 x 0.240 x 0.320
Cell length (Å)	a = 21.6603(6)	2θ range (°)	2.38 to 30.50
	b = 9.7970(3)	Reflections collected	23446
	c = 13.9906(3)	Indep. Refl. (R _{int})	7914 [R(int) = 0.0585]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.550 and -0.620
	β = 90	R1, wR2 (<i>I</i> > 2σ(<i>I</i>))	0.0367, 0.0619
	γ = 90	R1, wR2 (all data)	0.0599, 0.0693

2.3.12 - Synthesis of [(MesHN)(S)P(μ-N^tBu)]₂ (**3.12**)

Identical to the procedure for synthesis of **3.6**, **1.1** (0.255 g, 0.93 mmol), mesitylamine (0.26 cm³, 1.9 mmol) and elemental sulfur (0.089 g, 2.8 mmol) along with triethylamine

(0.26 cm³, 1.9 mmol) were used. The reaction was milled for 5.0 hours at 30 Hz. Toluene was added to extract product and, triethylammonium chloride and unreacted sulfur were filtered off. The toluene fraction was evaporated to dryness and the resulting solid was recrystallized in chloroform to yield colorless crystals. Yield: 0.140 g (28 %); ¹H NMR (CDCl₃, 400 MHz): δ 6.88 (s, 4H, *m*-ArH), 4.78 (s, 2H, N-H), 2.49 (s, 12H, *o*-ArCH₃), 2.25 (s, 6H, *p*-ArCH₃), 1.60 (s, 18H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 136.12 (s, N-ArC), 135.27 (s, *p*-ArC), 132.86 (s, *o*-ArC), 129.81 (s, *m*-ArC), 57.71 (s, C(CH₃)₃), 30.46 (s, C(CH₃)₃), 20.96 (s, *p*-CH₃), 20.88 (s, *o*-CH₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 45.42 (s); m.p. 204 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 3175 (N-H), 3125 (N-H); MS (EI) *m/z*: 537.24 [M+1]⁺; No satisfactory elemental analyses obtained.^{73,85,125,126}

Table 2.10. Crystal data and structure refinement for compound **3.12**.

Empirical Formula	C ₃₂ H ₅₈ ClN ₅ P ₂ S ₂	Volume (Å ³)	3772.5(3)
F _w	674.34 g/mol	Z	4
T (K)	100(2)	ρ _{calc} (g/cm ³)	1.187
λ (Å)	0.71073	μ, (mm ⁻¹)	0.325
Crystal System	Monoclinic	F(000)	1396
Space Group	P 1 21/n 1	Crystal Size (mm)	0.180 x 0.320 x 0.380
Cell length (Å)	a = 12.4877(6)	2θ range (°)	2.53 to 31.02
	b = 21.2753(2)	Reflections collected	71612
	c = 14.3760(7)	Indep. Refl. (R _{int})	12007 [R(int) = 0.0613]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.572 and -0.671
	β = 98.992(2)	R1, wR2 (<i>I</i> > 2σ(<i>I</i>))	0.0410, 0.0962
	γ = 90	R1, wR2 (all data)	0.0566, 0.1056

2.3.13 - Synthesis of [(MesHN)(Se)P(μ -N^tBu)]₂ (**3.13**)

Identical to the procedure for synthesis of **3.6**, **1.1** (0.265 g, 0.96 mmol), mesitylamine (0.27 cm³, 1.9 mmol) and elemental selenium (0.226 g, 2.9 mmol) along with triethylamine (0.27 cm³, 1.9 mmol) were used. The reaction was milled for 5.0 hours at 30 Hz. Toluene was added to extract product and, triethylammonium chloride and unreacted selenium were filtered off. The filtrate was concentrated and left to crystallize at room temperature. Yield: 0.169 g (28 %); ¹H NMR (C₆D₆, 400 MHz): δ 6.71 (s, 4H, *m*-ArH), 4.85 (s, 2H, N-H), 2.39 (s, 12H, *o*-ArCH₃), 2.08 (s, 6H, *p*-ArCH₃), 1.73 (s, 18H, C(CH₃)₃); ¹³C NMR (C₆D₆, 101 MHz): δ 137.24 (s, N-ArC), 133.38 (t, ⁵J_{P-C} = 2.0 Hz, *p*-ArC), 129.97 (s, *o*-ArC), 129.30 (s, *m*-ArC), 58.72 (s, C(CH₃)₃), 30.63 (t, ³J_{P-C} = 4.0 Hz, C(CH₃)₃), 21.49 (s, *p*-CH₃), 20.79 (s, *o*-CH₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 36.31 (s, ¹J_{P-Se} = 916.1 Hz, ²J_{P-P} = 8.9 Hz); m.p. 196 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 3294 (N-H), 3264 (N-H), 885 (P=Se); MS (EI) *m/z*: 633.13 [M+1]⁺; No satisfactory elemental analyses obtained.^{73,85,125,126}

Table 2.11. Crystal data and structure refinement for compound **3.13**.

Empirical Formula	C _{29.50} H ₄₆ N ₄ P ₂ Se ₂	Volume (Å ³)	3144.06(12)
F _w	676.56 g/mol	Z	4
T (K)	100(2)	ρ_{calc} (g/cm ³)	1.429
λ (Å)	0.71073	μ , (mm ⁻¹)	2.479
Crystal System	Monoclinic	F(000)	1396
Space Group	P 1 21/n 1	Crystal Size (mm)	0.237 x 0.281 x 0.349
Cell length (Å)	a = 12.4478(3)	2 θ range (°)	2.35 to 31.01

	$b = 12.6609(2)$	Reflections collected	48447
	$c = 20.8021(5)$	Indep. Refl. (R_{int})	9851 [$R(\text{int}) = 0.0721$]
Cell angles ($^{\circ}$)	$\alpha = 90$	Larg. Diff. Peak & hole ($\text{e}\text{\AA}^{-3}$)	1.027 and -1.105
	$\beta = 106.4599(9)$	R1, wR2 ($I > 2\sigma(I)$)	0.0411, 0.0921
	$\gamma = 90$	R1, wR2 (all data)	0.0672, 0.1059

2.4 - Syntheses of new compounds in Chapter 4

2.4.1 - Synthesis of $[\text{Ad}(\text{O})\text{CO}]\text{P}(\mu\text{-N}^t\text{Bu})_2$ (**4.3**)

To a 20 mL THF solution of **1.1** (0.550 g, 2.0 mmol), adamantane-1-carboxylic acid (0.721 g, 4.0 mmol) and triethylamine (0.56 cm³, 4.0 mmol) in THF was added dropwise at room temperature. The reaction mixture was left to stir overnight. The resulting ammonium salt was removed *via* filtration. THF was replaced with toluene to recrystallize the product. Yield: 0.341 g (30 %); ¹H NMR (C₆D₆, 400 MHz): δ 2.07 (d, ² $J_{\text{H-H}} = 2.0$ Hz, 12H, C(CH₂)₃), 1.90 (br s, 6H, CH), 1.60 (br s, 12H, CH₂), 1.37 (s, 18H, C(CH₃)₃); ¹³C NMR (C₆D₆, 101 MHz): δ 176.82 (s, C=O), 52.26 (t, ² $J_{\text{P-C}} = 8.6$ Hz, C(CH₃)₃), 41.36 (s, C(CH₂)₃), 39.21 (s, C(CH₂)₃), 36.81 (s, CH₂), 31.03 (t, ³ $J_{\text{P-C}} = 6.6$ Hz, C(CH₃)₃), 28.46 (s, CH); ³¹P-{¹H} NMR (C₆D₆, 162 MHz): δ 175.07 (s); m.p. 104 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1711 (C=O), 1217 (C-O); MS (EI) m/z : 563.31 [M+1]⁺; No satisfactory elemental analyses obtained.^{73,85,125,126}

2.4.2 - Synthesis of $[P(\mu\text{-}N^t\text{Bu})_2P(\mu\text{-}OC_6H_4(O)CO)]_2$ (**4.4**)

A mixture of **1.1** (1.100 g, 4.0 mmol), *p*-hydroxybenzoic acid (0.552 g, 4.0 mmol) and triethylamine (1.12 cm³, 8.0 mmol) were added into the miller jar along with 10 mm stainless steel ball. The mixture was milled at 30 Hz for 6.0 hours. The resultant mixture was transferred into a Schlenk flask in the glovebox. Toluene was added and ammonium salt was removed *via* filtration. Solvent was evaporated and pentane was added to dissolve residue and left to crystallize. Colorless crystals were obtained after leaving the solution stand at room temperature. Isolated crystalline yield: 0.676 g (50 %); ¹H NMR (CDCl₃, 400 MHz): δ 7.58 (d, ³J_{H-H} = 8.8 Hz, 4H, ArH adjacent to carbonyl group), 7.11 (d, ³J_{H-H} = 8.8 Hz, 4H, ArH), 1.43 (s, 36H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 165.22 (d, ²J_{P-C} = 4.0 Hz, C=O), 156.83 (d, ²J_{P-C} = 16.2 Hz, O-C), 131.36 (s, C(O)C-C), 125.58 (d, ³J_{P-C} = 4.0 Hz, C(O)-C), 122.39 (d, ³J_{P-C} = 3.0 Hz, O-C), 52.90 (t, ²J_{P-C} = 12.1 Hz, C(CH₃)₃), 31.26 (t, ³J_{P-C} = 6.1 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 142.96 (d, ²J_{P-P} = 22.7 Hz, P-OC(O)), 139.88 (d, ²J_{P-P} = 22.7 Hz, P-O); compound turned yellow at 270 °C and orange at 290 °C. did not melt even heated to 320 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1695 (C=O), 1601 (C=O); MS (EI) *m/z*: 681.24 [M+1]⁺; Anal. Calcd for C₃₀H₄₄N₄O₆P₄: C, 52.94; H, 6.52; N, 8.23. Found: C, 52.61; H, 6.55; N, 7.77%.

Table 2.12. Crystal data and structure refinement for compound **4.4**.

Empirical Formula	C ₁₅ H ₂₂ N ₂ O ₃ P ₂	Volume (Å ³)	880.7(6)
F _w	340.28 g/mol	Z	2
T (K)	296(2)	ρ _{calc} (g/cm ³)	1.283

λ (Å)	0.71073	μ , (mm ⁻¹)	0.260
Crystal System	Triclinic	F(000)	360
Space Group	P -1	Crystal Size (mm)	0.060 x 0.100 x 0.140
Cell length (Å)	a = 8.029(3)	2 θ range (°)	2.21 to 26.85
	b = 9.596(3)	Reflections collected	16328
	c = 11.972(4)	Indep. Refl. (R _{int})	3689 [R(int) = 0.1036]
Cell angles (°)	α = 76.811(8)	Larg. Diff. Peak & hole (eÅ ⁻³)	0.237 and -0.312
	β = 85.252(8)	R1, wR2 (<i>I</i> > 2 σ (<i>I</i>))	0.0554, 0.1047
	γ = 79.065(8)	R1, wR2 (all data)	0.1728, 0.1440

2.4.3 - Synthesis of [P(μ -N^{*t*}Bu)₂P(μ -OC₁₀H₆(O)CO)]₂ (**4.5**)

Identical to the procedure for synthesis of **4.4**, **1.1** (0.550 g, 2.0 mmol), 6-hydroxy-2-naphthoic acid (0.377 g, 2.0 mmol) and triethylamine (0.56 cm³, 4.0 mmol) were used. The mixture was then milled at 30 Hz for 8 hours. Toluene (30 mL) and THF (~5 mL) were added to extract product. Ammonium chloride was filtered off and the resulting filtrate was concentrated to saturation. The saturated solution was left to crystallize at room temperature to yield colorless needle-like crystals. Isolated crystalline yield: 0.297 g (38 %); ¹H NMR (CDCl₃, 400 MHz): δ 7.71 (s, 2H, **H3**), 7.61 and 7.60 (overlap of two singlets, 4H, **H5** and **H4**), 7.35 (d, ³J_{H-H} = 8.8 Hz, 2H, **H2**), 7.23 (d, ⁴J_{H-H} = 8.4 Hz, 2H, **H6**), 7.11 (d, ³J_{H-H} = 8.8 Hz, 2H, **H1**), 1.51 (s, 36H, **H7**); ¹³C NMR (CDCl₃, 101 MHz): δ 164.83 (d, ²J_{P-C} = 6.1 Hz, **C11**), 151.79 (d, ²J_{P-C} = 16.2 Hz, **C1**), 135.95 (s, **C3**), 131.38 (s, **C9**), 129.86 (s, **C7**), 129.26 (s, **C8**), 127.07 (s, **C4**), 125.97 (d, ³J_{P-C} = 3.0 Hz,

C6), 125.22 (s, **C5**), 124.32 (s, **C10**), 119.40 (d, $^3J_{P-C} = 5.1\text{ Hz}$, **C2**), 53.01 (t, $^2J_{P-C} = 12.6\text{ Hz}$, **C12**), 30.96 (t, $^3J_{P-C} = 6.1\text{ Hz}$, **C13**); $^{31}\text{P}\{-^1\text{H}\}$ NMR (CDCl_3 , 162 MHz): δ 145.90 (d, $^2J_{P-P} = 22.7\text{ Hz}$, **P-OC(O)**), 141.46 (d, $^2J_{P-P} = 22.7\text{ Hz}$, **P-O**); compound turned yellow at 270 °C and orange at 290 °C. did not melt even heated to 300 °C; IR (mineral oil, NaCl) ν (cm^{-1}): 1686 (C=O), 1628 (C=O); MS (EI) m/z : 781.26 $[\text{M}+1]^+$; Anal. Calcd for $\text{C}_{38}\text{H}_{48}\text{N}_4\text{O}_6\text{P}_4 \cdot \text{H}_2\text{O}$: C, 57.14; H, 6.31; N, 7.01. Found: C, 56.86; H, 6.39; N, 6.63%.

Table 2.13. Crystal data and structure refinement for compound **4.5**.

Empirical Formula	$\text{C}_{38}\text{H}_{48}\text{N}_4\text{O}_6\text{P}_4$	Volume ($\text{\AA}^3$)	2005.90(9)
F_w	780.68 g/mol	Z	2
T (K)	296(2)	ρ_{calc} (g/cm^3)	1.293
λ ($\text{\AA}$)	1.54178	μ , (mm^{-1})	2.142
Crystal System	Triclinic	F(000)	824
Space Group	P -1	Crystal Size (mm)	0.040 x 0.100 x 0.360
Cell length ($\text{\AA}$)	$a = 7.0573(2)$	2θ range ($^\circ$)	2.60 to 66.64
	$b = 17.0994(4)$	Reflections collected	32944
	$c = 18.2449(5)$	Indep. Refl. (R_{int})	7059 [$R_{\text{int}} = 0.0725$]
Cell angles ($^\circ$)	$\alpha = 68.9247(16)$	Larg. Diff. Peak & hole ($\text{e}\text{\AA}^{-3}$)	0.832 and -0.438
	$\beta = 89.7535(16)$	R1, wR2 ($I > 2\sigma(I)$)	0.0741, 0.2042
	$\gamma = 78.2796(15)$	R1, wR2 (all data)	0.0976, 0.2236

2.4.4 - Synthesis of $[\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\mu\text{-}m\text{-OC(O)C}_6\text{H}_4(\text{O})\text{CO})]_2$ (**4.6**)

Identical to the procedure for synthesis of **4.4**, **1.1** (0.550 g, 2.0 mmol), isophthalic acid (0.332 g, 2.0 mmol) and triethylamine (0.56 cm³, 4.0 mmol) were used. The mixture was milled for 2.0 hours at 30 Hz. THF was added and ammonium salt was removed *via* filtration. THF was replaced with pentane for recrystallization to afford colorless crystals. Yield: 0.420 g (57 %) ¹H NMR (CDCl₃, 400 MHz): δ 8.71 (s, 2H, *H* between two carbonyl groups), 8.41 (d, ³J_{H-H} = 8.0 Hz, 4H, *o*-Ar*H*), 7.60 (t, ³J_{H-H} = 8.0 Hz, 2H, *m*-Ar*H*), 1.48 (s, 36H, C(CH₃)₃); ¹³C NMR (CDCl₃, 100 MHz): δ 166.05 (s, C=O), 135.87 (s, *o*-ArC), 130.98 (s, C-C=O), 130.70 (s, ArC between two carbonyl groups), 129.10 (s, *m*-ArC), 53.18 (t, ²J_{P-C} = 10.6 Hz, C(CH₃)₃), 31.19 (t, ³J_{P-C} = 6.0 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 164.77 (s); m.p. 198-200 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1701 (C=O), 1692 (C=O); MS (EI) *m/z*: 737.21 [M+1]⁺; No satisfactory elemental analyses obtained.^{73,85,125,126}

Table 2.14. Crystal data and structure refinement for compound **4.6**.

Empirical Formula	C ₃₄ H ₄₄ N ₄ O ₈ P ₄	Volume (Å ³)	1879.0(14)
F _w	736.59 g/mol	Z	2
T (K)	103(2)	ρ _{calc} (g/cm ³)	1.302
λ (Å)	0.71073	μ, (mm ⁻¹)	0.253
Crystal System	Triclinic	F(000)	776
Space Group	P -1	Crystal Size (mm)	0.080 x 0.240 x 0.400
Cell length (Å)	a = 12.350(5)	2θ range (°)	1.72 to 25.46
	b = 13.071(5)	Reflections collected	30381
	c = 13.093(6)	Indep. Refl. (R _{int})	6893 [R(int) = 0.1582]
Cell angles (°)	α = 69.638(10)	Larg. Diff. Peak & hole (eÅ ⁻³)	0.436 and -0.513
	β = 72.217(10)	R1, wR2 (<i>I</i> > 2σ(<i>I</i>))	0.0662, 0.1441
	γ = 79.188(10)	R1, wR2 (all data)	0.1432, 0.1863

2.4.5 - Synthesis of $[P(\mu\text{-}N^t\text{Bu})_2P(\mu\text{-}p\text{-OC(O)C}_6\text{H}_4(\text{O})\text{CO})]_2$ (**4.7**)

Identical to the procedure for synthesis of **4.4**, **1.1** (1.375 g, 5.0 mmol), terephthalic acid (0.830 g, 5.0 mmol) and triethylamine (1.40 cm³, 10.0 mmol) were used and the mixture was milled for 6 hours at 30 Hz. Yield: 1.588 g (86.0%); ¹H NMR (CDCl₃, 400 MHz): δ 8.20 (s, 8H, ArH), 1.36 (s, 36H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 164.84 (s, C=O), 135.21 (s, C-C=O), 130.57 (s, ArC), 52.50 (t, ²J_{P-C} = 8.6 Hz, C(CH₃)₃), 30.96 (t, ³J_{P-C} = 6.1 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 188.03 (s); m.p. 230-232 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1692 (C=O); MS (EI) *m/z*: 737.22 [M+1]⁺; Anal. Calcd for C₃₂H₄₄N₄O₈P₄·H₂O: C, 50.93; H, 6.14; N, 7.42. Found: C, 50.97; H, 6.81; N, 7.13%.

Table 2.15. Crystal data and structure refinement for compound **4.7**.

Empirical Formula	C ₃₄ H ₄₄ N ₄ O ₈ P ₄	Volume (Å ³)	910.01(8)
F _w	736.59 g/mol	Z	1
T (K)	103(2)	ρ _{calc} (g/cm ³)	1.344
λ (Å)	0.71073	μ, (mm ⁻¹)	0.261
Crystal System	Triclinic	F(000)	388
Space Group	P -1	Crystal Size (mm)	0.100 x 0.120 x 0.220
Cell length (Å)	a = 6.9000(3)	2θ range (°)	1.49 to 31.72
	b = 9.7224(5)	Reflections collected	27790
	c = 14.4112(8)	Indep. Refl. (R _{int})	6136 [R(int) = 0.0808]

Cell angles (°)	$\alpha = 76.124(3)$	Larg. Diff. Peak & hole ($\text{e}\text{\AA}^{-3}$)	0.530 and -0.676
	$\beta = 76.805(3)$	R1, wR2 ($I > 2\sigma(I)$)	0.0487, 0.1256
	$\gamma = 81.922(3)$	R1, wR2 (all data)	0.0856, 0.1604

2.4.6 - Synthesis of $[\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\mu\text{-}m\text{-OC(O)C}_6\text{H}_3(^t\text{Bu})(\text{O})\text{CO})]_2$ (**4.8**)

Identical to the procedure for synthesis of **4.4**, **1.1** (0.275 g, 1.0 mmol), 5-*tert*-butylisophthalic acid (0.222 g, 1.0 mmol) and triethylamine (0.28 cm³, 2.0 mmol) were used and the mixture was milled for 3 hours at 30 Hz. Yield: 0.238 g (56 %); ¹H NMR (CDCl₃, 400 MHz): δ 8.56 (s, 2H, ArH), 8.45 (s, 4H, *m*-ArH), 1.47 (s, 36H, C(CH₃)₃ on P₂N₂ rings), 1.37 (s, 18H, C(CH₃)₃ on aromatic rings); ¹³C NMR (CDCl₃, 101 MHz): δ 166.48 (s, C=O), 152.67 (s, ArC-C(CH₃)₃), 132.96 (s, *o*-ArC), 130.74 (s, ArC-C=O), 128.15 (s, ArC between two carbonyl groups), 53.12 (t, ²J_{P-C} = 10.5 Hz, C(CH₃)₃), 31.25 (s, C(CH₃)₃ on P₂N₂ rings), 31.18 (t, ³J_{P-C} = 7.1 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 165.42 (s); m.p. 250 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1697 (C=O), 1680 (C=O), 1605 (C=O), 1587 (C=O); MS (EI) m/z : 849.34 [M+1]⁺;

Table 2.16. Crystal data and structure refinement for compound **4.8**.

Empirical Formula	C ₄₀ H ₆₀ N ₄ O ₈ P ₄	Volume (Å ³)	4619.08(17)
F _w	848.80 g/mol	Z	4
T (K)	100(2)	ρ_{calc} (g/cm ³)	1.221
λ (Å)	0.71073	μ , (mm ⁻¹)	0.214
Crystal System	Monoclinic	F(000)	1808

Space Group	P 1 21/c 1	Crystal Size (mm)	0.305 x 0.393 x 0.461
Cell length (Å)	a = 13.2042(3)	2θ range (°)	2.29 to 28.70
	b = 12.7089(3)	Reflections collected	78642
	c = 27.7108(5)	Indep. Refl. (R _{int})	11905[R(int) = 0.0672]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.938 and -0.379
	β = 96.6294(8)	R1, wR2 (I>2σ(I))	0.0529, 0.1153
	γ = 90	R1, wR2 (all data)	0.0711, 0.1258

2.4.7 - Synthesis of [P(μ-N^tBu)₂P(μ-*p*-OC₆H₄C(O)O)]₂ (**4.10**)

Compound **4.4** was generated *in situ* from the reported procedure above, using **1.1** (1.100 g, 4.0 mmol) and *p*-hydroxybenzoic acid (0.552 g, 4.0 mmol), triethylamine (1.12 cm³, 8.0 mmol). Elemental sulfur (0.128 g, 4.0 mmol) was added and the reaction mixture was heated to reflux overnight. Unreacted sulfur was filtered to obtain clear solution. Upon leaving to stand at room temperature, colorless crystals were obtained. Yield: 1.06 g (71 %); ¹H NMR (CDCl₃, 400 MHz): δ 7.57 (d, ³J_{H-H} = 8.8 Hz, 4H, ArH adjacent to carbonyl group), 7.33 (dd, ⁴J_{P-H} = 1.6 Hz, ³J_{H-H} = 8.8 Hz, 4H, ArH), 1.54 (s, 36H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 164.96 (d, ²J_{P-C} = 6.1 Hz, C=O), 155.36 (d, ²J_{P-C} = 16.3 Hz, O-ArC), 131.82 (s, C(O)C-C), 126.32 (s, C(O)-C), 121.60 (d, ³J_{P-C} = 5.1 Hz, O-C-C), 55.49 (d, ²J_{P-C} = 11.1 Hz, C(CH₃)₃), 31.11 (t, ³J_{P-C} = 5.1 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 107.28 (d, ²J_{P-P} = 17.8 Hz, P-OC(O)), 52.58 (d, ²J_{P-P} = 19.4 Hz, P=S); m.p. 190 °C; MS (EI) *m/z*: 745.17 [M+1]⁺;

Table 2.17. Crystal data and structure refinement for compound **4.10**.

Empirical Formula	C ₁₉ H ₃₀ N ₂ O ₄ P ₂ S	Volume (Å ³)	2315.1(15)
F _w	444.45 g/mol	Z	4
T (K)	203(2)	ρ _{calc} (g/cm ³)	1.275
λ (Å)	0.71073	μ, (mm ⁻¹)	0.304
Crystal System	Monoclinic	F(000)	944
Space Group	P 1 21/n 1	Crystal Size (mm)	0.160 x 0.180 x 0.260
Cell length (Å)	a = 8.664(3)	2θ range (°)	1.74 to 29.43
	b = 11.5481(5)	Reflections collected	33006
	c = 23.1981(9)	Indep. Refl. (R _{int})	6301 [R(int) = 0.0966]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.417 and -0.366
	β = 94.071(13)	R1, wR2 (I > 2σ(I))	0.0643, 0.1701
	γ = 90	R1, wR2 (all data)	0.1343, 0.2113

2.4.8 - Synthesis of [(S)P(μ-N^tBu)₂P(O)(μ-*p*-OC₆H₄C(O)O)]₂ (**4.10a**)

Compound **4.10** was prepared *in situ* from **4.4** (0.308 g, 0.45 mmol) and elemental sulfur (0.029 g, 0.91 mmol) according to the above procedure. *Tert*-butyl hydroperoxide (0.13 cm³, 0.93 mmol) was dissolved in 5 mL THF and added dropwise into the solution at 0 °C. The reaction mixture was left to stir at room temperature overnight. The reaction mixture was filtered and concentrated to saturation and left to crystallize at room temperature. Yield: negligible; crystalline yield barely sufficient for analysis reported as follow; ¹H NMR (CDCl₃, 400 MHz): δ 7.71 (d, ³J_{H-H} = 8.8 Hz, 4H, ArH adjacent to carbonyl group), 7.39 (d, ³J_{H-H} = 7.2 Hz, 4H, ArH), 1.64 (s, 18H, C(CH₃)₃); ³¹P-{¹H}

NMR (CDCl₃, 162 MHz): δ 38.67 (d, $^2J_{P-P}$ = 45.4 Hz, **P=S**), -9.58 (d, $^2J_{P-P}$ = 43.7 Hz, **P=O**); MS (EI) m/z : 777.16 [M+1]⁺;

Table 2.18. Crystal data and structure refinement for compound **4.10a**.

Empirical Formula	C ₃₈ H ₆₀ N ₄ O _{9.92} P ₄ S _{2.08}	Volume (Å ³)	2266.7(7)
F _w	922.18 g/mol	Z	2
T (K)	110(2)	ρ_{calc} (g/cm ³)	1.351
λ (Å)	0.71073	μ , (mm ⁻¹)	0.320
Crystal System	Monoclinic	F(000)	977
Space Group	P 1 21/n 1	Crystal Size (mm)	0.060 x 0.080 x 0.200
Cell length (Å)	a = 8.4577(14)	2 θ range (°)	2.49 to 29.20
	b = 11.631(2)	Reflections collected	29843
	c = 23.134(4)	Indep. Refl. (R _{int})	6120 [R(int) = 0.1056]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.659 and -0.605
	β = 95.104(5)	R1, wR2 ($I > 2\sigma(I)$)	0.0772, 0.1532
	γ = 90	R1, wR2 (all data)	0.1334, 0.1789

2.4.9 - Synthesis of [(S)P(μ -N^tBu)₂P(S)(μ -p-OC₆H₄C(O)O)]₂ (**4.10b**)

To a 15 mL THF solution containing **4.10** (0.296 g, 0.4 mmol), elemental sulfur (0.029 g, 0.8 mmol) was added at room temperature. The reaction mixture was stirred overnight. Unreacted sulfur was removed *via* filtration and the clear solution obtained was left to stand at room temperature for recrystallization. Yield: 0.036 g (11 %); ¹H NMR (CDCl₃, 400 MHz): δ 7.66 (d, $^3J_{H-H}$ = 8.4 Hz, 4H, Ar**H** adjacent to carbonyl group), 7.35 (d, $^3J_{H-H}$ = 7.6 Hz, 4H, Ar**H**), 1.72 (s, 36H, C(**CH**₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ

41.87 (d, $^2J_{\text{P-P}} = 25.9$ Hz, S= P-OC(O)), 37.29 (d, $^2J_{\text{P-P}} = 25.9$ Hz, S= P-O); MS (EI) m/z : 809.11 $[\text{M}+1]^+$;

Table 2.19. Crystal data and structure refinement for compound **4.10b**.

Empirical Formula	$\text{C}_{38}\text{H}_{60}\text{N}_4\text{O}_8\text{P}_4\text{S}_4$	Volume ($\text{\AA}^3$)	2292.02(9)
F_w	953.02 g/mol	Z	2
T (K)	100(2)	ρ_{calc} (g/cm^3)	1.381
λ ($\text{\AA}$)	0.71073	μ , (mm^{-1})	0.400
Crystal System	Monoclinic	$F(000)$	1008
Space Group	$P 1 2_1/n 1$	Crystal Size (mm)	0.106 x 0.181 x 0.337
Cell length ($\text{\AA}$)	$a = 8.9577(2)$	2θ range ($^\circ$)	2.44 to 28.00
	$b = 11.3813(3)$	Reflections collected	37111
	$c = 22.4834(5)$	Indep. Refl. (R_{int})	5523 [$R(\text{int}) = 0.0628$]
Cell angles ($^\circ$)	$\alpha = 90$	Larg. Diff. Peak & hole ($\text{e}\text{\AA}^{-3}$)	0.974 and -0.675
	$\beta = 90.6903(9)$	$R1, wR2$ ($I > 2\sigma(I)$)	0.0445, 0.0860
	$\gamma = 90$	$R1, wR2$ (all data)	0.0612, 0.0948

2.4.10 - Synthesis of $[\mu\text{-P}(\mu\text{-N}^t\text{Bu})_2\text{P}]_4(\mu\text{-}p\text{-OC}_6\text{H}_4\text{C(O)O})_4$ (**4.11**)

A 25 mL THF solution of **1.1** (0.550 g, 2.0 mmol) and triethylamine (0.56 cm^3 , 4.0 mmol) was first prepared. To a 25 mL THF solution of *p*-hydroxybenzoic acid (0.552 g,

4.0 mmol), the pre-prepared THF solution was added dropwise at -78 °C. The reaction mixture was left to gradually warm to room temperature and left to stir for 3 hours. Another batch of 25 mL THF solution of **1.1** (0.550 g, 2.0 mmol) and triethylamine (0.56 cm³, 4.0 mmol) was added dropwise at -78 °C into the reaction mixture. Upon complete addition, the reaction mixture was stirred overnight. Solvent was removed under reduced pressure and hexane was added to extract the product. The filtrate was subsequently concentrated and left to crystallize at 5 °C. The product was collected as colorless crystals. Yield: 0.436 g (80 %); ¹H NMR (CDCl₃, 400 MHz): δ 8.11 (d, ³J_{H-H} = 8.4 Hz, 8H, ArH adjacent to carbonyl group), 7.17 (d, ³J_{H-H} = 8.4 Hz, 8H, ArH), 1.39 (s, 72H, C(CH₃)₃); ¹H NMR (tol-d₈, 400 MHz): δ 8.25 (d, ³J_{H-H} = 8.4 Hz, 8H, ArH adjacent to carbonyl group), 7.12 (d, ³J_{H-H} = 8.8 Hz, 8H, ArH), 1.33 (s, 36H, C(CH₃)₃), 1.24 (s, 36H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 165.57 (s, C=O), 158.74 (s, O-ArC), 132.23 (s, C(O)C-C), 125.56 (s, C(O)-C), 120.18 (t, ³J_{P-C} = 5.6 Hz, O-C-C), 52.55-52.18 (m, 2 sets of C(CH₃)₃), 31.64 (t, ³J_{P-C} = 5.6 Hz, C(CH₃)₃), 31.00 (t, ³J_{P-C} = 6.1 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 179.75 (s, P-OC(O)), 150.82 (s, P-O); m.p. 182-184 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1699 (C=O), 1597 (C=O); MS (EI) m/z: 1361.45 [M+1]⁺;

Table 2.20. Crystal data and structure refinement for compound **4.11**.

Empirical Formula	C ₁₂₀ H ₁₇₆ N ₁₆ O ₂₄ P ₁₆	Volume (Å ³)	3892.28(9)
F _w	2722.28 g/mol	Z	1
T (K)	103(2)	ρ _{calc} (g/cm ³)	1.161
λ (Å)	1.54178	μ, (mm ⁻¹)	2.134
Crystal System	Monoclinic	F(000)	1440
Space Group	P 2 1/c	Crystal Size (mm)	0.180 x 0.100 x 0.060
Cell length (Å)	a = 13.1677(2)	2θ range (°)	2.744 to 66.632
	b = 9.17990(10)	Reflections collected	33106

	$c = 32.2002(4)$	Indep. Refl. (R_{int})	6855 [$R(\text{int}) = 0.0596$]
Cell angles ($^{\circ}$)	$\alpha = 90$	Larg. Diff. Peak & hole ($\text{e}\text{\AA}^{-3}$)	1.371 and -0.668
	$\beta = 90.2116(9)$	R1, wR2 ($I > 2\sigma(I)$)	0.1215, 0.3488
	$\gamma = 90$	R1, wR2 (all data)	0.1440, 0.3785

2.5 - Syntheses of new compounds in Chapter 5

2.5.1 - Synthesis of $[(p\text{-OC}_6\text{H}_4\text{CO}_2\text{Et})\text{P}(\mu\text{-N}^t\text{Bu})_2]_2$ (**5.1**)

Compound **1.1** (0.779 g, 2.8 mmol) and triethylamine (0.79 cm³, 5.6 mmol) were dissolved in 20 mL THF. Ethyl 4-hydroxybenzoate (0.938 g, 5.6 mmol) was dissolved in 20 mL THF and added dropwise at room temperature. The reaction mixture was left to stir overnight. THF was removed under reduced pressure and hexane was added to extract the product. The solution was filtered, and the filtrate was concentrated to saturation. The saturated solution was left to crystallize and afford a mixture of *cis* and *trans* isomers for the first few batches of crystals, followed by pure *cis*-**5.1**. ***cis***: Yield: 0.913 g (61 %); ¹H NMR (CDCl₃, 400 MHz): δ 7.99 (d, ³*J*_{H-H} = 8.8 Hz, 4H, *m*-ArH), 7.16 (d, ³*J*_{H-H} = 8.4 Hz, 4H, *o*-ArH), 4.36 (q, ³*J*_{H-H} = 7.2 Hz, 4H, CH₂CH₃), 1.34 (s, 18H, C(CH₃)₃), 1.38 (t, ³*J*_{H-H} = 4.4 Hz, 6H, CH₂CH₃); ¹³C NMR (CDCl₃, 101 MHz): δ 166.43 (s, C=O), 157.70 (s, O-ArC), 131.32 (s, *m*-ArC), 125.44 (s, ArC-C=O), 120.42 (s, *o*-ArC), 60.94 (s, O-CH₂), 52.29 (s, C(CH₃)₃), 31.43 (t, ³*J*_{P-C} = 4.5 Hz, C(CH₃)₃), 14.52 (s, CH₂CH₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 144.22 (s) IR (mineral oil, NaCl) ν (cm⁻¹): 1717 (C=O), 1601 (C=O), 1503 (C=C); MS (EI) *m/z*: 535.21 [M+1]⁺; ***trans***: Yield: negligible, sufficient for NMR analysis only; ¹H NMR (C₆D₆, 400 MHz): δ 8.03 (d, ³*J*_{H-}

$_{\text{H}} = 8.8\text{Hz}$, 4H, *m*-Ar H), 7.21 (d, $^3J_{\text{H-H}} = 9.2\text{ Hz}$, 4H, *o*-Ar H), 4.36 (q, $^3J_{\text{H-H}} = 7.2\text{ Hz}$, 4H, CH_2CH_3), 1.25 (s, 18H, $\text{C}(\text{CH}_3)_3$), 1.38 (t, $^3J_{\text{H-H}} = 7.2\text{ Hz}$, 6H, CH_2CH_3); $^{31}\text{P}\{-^1\text{H}\}$ NMR (C_6D_6 , 162 MHz): δ 234.44 (s);

2.5.2 - Synthesis of $[(p\text{-OC}_6\text{H}_4\text{CO}_2\text{Et})(\text{O})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (**5.2**)

Compound **5.1** was generated *in situ* from the procedure described above, with **1.1** (0.189 g, 0.69 mmol), triethylamine (0.20 cm³, 1.4 mmol) and ethyl 4-hydroxybenzoate (0.228 g, 1.4 mmol). *Tert*-butyl hydroperoxide (0.20 cm³, 1.4 mmol) in 2 mL THF was added dropwise at 0 °C. The reaction mixture was gradually warmed to room temperature and stirred for 6.0 hours. THF was removed under reduced pressure and hexane was added to extract the product. The hexane fraction was evaporated to dryness, resulting in white precipitate. The white solid obtained was washed with ether and vacuumed dried. Yield: 0.129 g (33 %); ^1H NMR (CDCl_3 , 400 MHz): δ 8.08 (d, $^3J_{\text{H-H}} = 8.8\text{ Hz}$, 4H, *m*-Ar H), 7.42 (d, $^3J_{\text{H-H}} = 8.8\text{ Hz}$, 4H, *o*-Ar H), 4.39 (q, $^3J_{\text{H-H}} = 7.1\text{ Hz}$, 4H, CH_2CH_3), 1.44 (s, 18H, $\text{C}(\text{CH}_3)_3$), 1.40 (t, $^3J_{\text{H-H}} = 7.0\text{ Hz}$, 6H, CH_2CH_3); ^{13}C NMR (CDCl_3 , 101 MHz): δ 165.83 (s, $\text{C}=\text{O}$), 154.82 (s, P-OC), 131.66 (s, *m*-Ar C), 127.74 (s, Ar $\text{C}-\text{C}=\text{O}$), 121.31 (t, $^3J_{\text{P-C}} = 3.0\text{ Hz}$, *o*-Ar C), 61.31 (s, O- CH_2), 56.27 (s, $\text{C}(\text{CH}_3)_3$), 30.54 (t, $^3J_{\text{P-C}} = 4.5\text{ Hz}$, $\text{C}(\text{CH}_3)_3$), 14.46 (s, CH_2CH_3); $^{31}\text{P}\{-^1\text{H}\}$ NMR (CDCl_3 , 162 MHz): δ -8.21 (s);

2.5.3 - Synthesis of [(*p*-OC₆H₄CO₂Et)(S)P(μ -N^{*t*}Bu)]₂ (**5.3**)

A mixture of **1.1** (0.151 g, 0.55 mmol), ethyl 4-hydroxybenzoate (0.183 g, 1.10 mmol) and elemental sulfur (0.053 g, 1.65 mmol) were added into milling jar along with triethylamine (0.15 cm³, 1.10 mmol) and 10 mm stainless ball. The reaction was milled for 5.0 hours at 30 Hz. THF was added to extract the product and the insoluble ammonium chloride was filtered off. The resulting filtrate was evaporated to yield white solid. The white solid was recrystallized in methanol to obtain single crystals of *cis*-**5.3**. Crystals from methanol, *cis*: Yield: 0.240 g (73 %); ¹H NMR (CDCl₃, 400 MHz): δ 8.07 (d, ³J_{H-H} = 8.4 Hz, 4H, *m*-ArH), 7.32 (d, ³J_{H-H} = 8.8 Hz, 4H, *o*-ArH), 4.37 (q, ³J_{H-H} = 7.2 Hz, 4H, CH₂CH₃), 1.62 (s, 18H, C(CH₃)₃), 1.39 (t, ³J_{H-H} = 7.2 Hz, 6H, CH₂CH₃); ¹³C NMR (CDCl₃, 101 MHz): δ 165.85 (s, C=O), 154.84 (s, P-OC), 131.29 (s, *m*-ArC), 127.90 (s, ArC-C=O), 121.70 (s, *o*-ArC), 61.28 (s, O-CH₂), 57.90 (s, C(CH₃)₃), 30.18 (t, ³J_{P-C} = 4.5 Hz, C(CH₃)₃), 14.46 (s, CH₂CH₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 45.34 (s); m.p. 137 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1715 (C=O), 1599 (C=O), 770 (P=S); MS (EI) *m/z*: 599.17 [M+1]⁺;

Table 2.21. Crystal data and structure refinement for *cis*-**5.3**.

Empirical Formula	C ₂₆ H ₃₆ N ₂ O ₆ P ₂ S ₂	Volume (Å ³)	1478.2(5)
F _w	598.63 g/mol	Z	2
T (K)	100(2)	ρ _{calc} (g/cm ³)	1.345
λ (Å)	0.71073	μ, (mm ⁻¹)	0.330
Crystal System	Triclinic	F(000)	632
Space Group	P -1	Crystal Size (mm)	0.200 x 0.280 x 0.380

Cell length (Å)	a = 9.5524(19)	2θ range (°)	2.34 to 31.03
	b = 12.928(2)	Reflections collected	43310
	c = 13.488(2)	Indep. Refl. (R _{int})	9380 [R(int) = 0.0471]
Cell angles (°)	α = 96.374(6)	Larg. Diff. Peak & hole (eÅ ⁻³)	0.460 and -0.357
	β = 109.182(6)	R1, wR2 (I>2σ(I))	0.0377, 0.0870
	γ = 105.620(7)	R1, wR2 (all data)	0.0513, 0.0948

2.5.4 - Synthesis of [(*p*-OC₆H₄CO₂Et)(Se)P(*μ*-N^{*t*}Bu)]₂ (**5.4**)

Identical to synthetic procedure of **5.3**, **1.1** (0.215 g, 0.78 mmol), ethyl 4-hydroxybenzoate (0.259 g, 1.56 mmol), elemental selenium (0.185 g, 2.34 mmol) and triethylamine (0.22 cm³, 1.56 mmol) were used. The reaction mixture was milled for 6.0 hours at 30 Hz. Toluene was added to extract product and filtered. The toluene residue was subjected to THF extraction. The toluene fraction was concentrated and left to crystallize, yielding *cis* isomer of **5.4** at room temperature. The *trans* isomer was obtained from recrystallization of the THF fraction. Crystals from Toluene, *cis*: Yield: 0.340 g (63 %); ¹H NMR (CDCl₃, 400 MHz): δ 8.06 (d, ³J_{H-H} = 7.2 Hz, 4H, *m*-ArH), 7.33 (d, ³J_{H-H} = 8.0 Hz, 4H, *o*-ArH), 4.37 (q, ³J_{H-H} = 7.2 Hz, 4H, CH₂CH₃), 1.57 (s, 18H, C(CH₃)₃), 1.39 (t, ³J_{H-H} = 7.2 Hz, 6H, CH₂CH₃); ¹³C NMR (CDCl₃, 101 MHz): δ 165.84 (s, C=O), 154.91 (d, ²J_{P-C} = 10.0 Hz, P-OC), 131.28 (s, *m*-ArC), 128.01 (s, ArC-C=O), 121.88 (d, ³J_{P-C} = 5.1 Hz, *o*-ArC), 61.31 (s, O-CH₂), 58.70 (s, C(CH₃)₃), 30.26 (t, ³J_{P-C} = 4.0 Hz, C(CH₃)₃), 14.46 (s, CH₂CH₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 39.12 (s, ¹J_{P-Se} = 987.5 Hz); m.p. 125 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1715 (C=O), 1672 (C=O), 1599 (C=O), 897 (P=Se); MS (EI) *m/z*: 695.03 [M+1]⁺; Anal. Calcd for

C₂₆H₃₆N₂O₆P₂Se₂ C, 45.10; H, 5.24; N, 4.05. Found: C, 45.19; H, 5.64; N, 4.05%. Crystals from THF, **trans**: Yield: 0.027 g (5 %); ¹H NMR (C₆D₆, 400 MHz): δ 8.11 (d, ³J_{H-H} = 8.8 Hz, 4H, *m*-Ar**H**), 7.35 (d, ³J_{H-H} = 7.2 Hz, 4H, *o*-Ar**H**), 4.10 (q, ³J_{H-H} = 7.2 Hz, 4H, **CH**₂CH₃), 1.54 (s, 18H, C(**CH**₃)₃), 1.01 (t, ³J_{H-H} = 7.2 Hz, 6H, CH₂**CH**₃); ¹³C NMR (C₆D₆, 101 MHz): δ 165.83 (s, **C=O**), 155.18 (s, P-OC), 131.46 (s, *m*-Ar**C**), 128.40 (s, Ar**C**-C=O), 121.74 (t, ³J_{P-C} = 2.5 Hz, *o*-Ar**C**), 61.28 (s, O-**CH**₂), 58.99 (s, C(CH₃)₃), 30.79 (t, ³J_{P-C} = 4.5 Hz, C(CH₃)₃), 14.46 (s, CH₂CH₃); ³¹P-{¹H} NMR (C₆D₆, 162 MHz): δ 45.87 (s); MS (EI) *m/z*: 695.05 [M+1]⁺;

Table 2.22. Crystal data and structure refinement for *cis*-**5.4**.

Empirical Formula	C ₂₆ H ₃₆ N ₂ O ₆ P ₂ Se ₂	Volume (Å ³)	1472.44(14)
F _w	692.43 g/mol	Z	2
T (K)	100(2)	ρ _{calc} (g/cm ³)	1.562
λ (Å)	0.71073	μ, (mm ⁻¹)	2.662
Crystal System	Triclinic	F(000)	704
Space Group	P -1	Crystal Size (mm)	0.140 x 0.160 x 0.240
Cell length (Å)	a = 9.8576(5)	2θ range (°)	2.30 to 33.74
	b = 12.6046(7)	Reflections collected	46012
	c = 13.2638(7)	Indep. Refl. (R _{int})	11717 [R(int) = 0.0653]
Cell angles (°)	α = 95.4747(19)	Larg. Diff. Peak & hole (eÅ ⁻³)	0.741 and -0.818
	β = 108.5386(16)	R1, wR2 (<i>I</i> > 2σ(<i>I</i>))	0.0432, 0.0904
	γ = 105.8890(16)	R1, wR2 (all data)	0.0795, 0.1020

Table 2.23. Crystal data and structure refinement for *trans*-**5.4**.

Empirical Formula	C ₂₆ H ₃₆ N ₂ O ₆ P ₂ Se ₂	Volume (Å ³)	733.52(5)
F _w	692.43 g/mol	Z	1
T (K)	103(2)	ρ _{calc} (g/cm ³)	1.568
λ (Å)	0.71073	μ, (mm ⁻¹)	2.671
Crystal System	Triclinic	F(000)	352

Space Group	P -1	Crystal Size (mm)	0.120 x 0.160 x 0.280
Cell length (Å)	a = 8.4404(3)	2θ range (°)	1.98 to 31.26
	b = 9.2811(4)	Reflections collected	21557
	c = 10.9138(4)	Indep. Refl. (R _{int})	4752 [R(int) = 0.0467]
Cell angles (°)	α = 73.7289(15)	Larg. Diff. Peak & hole (eÅ ⁻³)	0.520 and -0.433
	β = 73.7170(14)	R1, wR2 (I>2σ(I))	0.0265, 0.0605
	γ = 65.5050(16)	R1, wR2 (all data)	0.0345, 0.0631

2.5.5 - Synthesis of [(P(μ -N^tBu))₂(μ -3,5-C₆H₃O₂(CO₂Me))]₂ (5.5)

To a mixture of **1.1** (1.38 g, 5.0 mmol) and triethylamine (1.4 cm³, 10.0 mmol) in THF, methyl 3,5-dihydroxybenzoate (0.841 g, 5.0 mmol) in THF was added dropwise at room temperature and brought to reflux overnight. The reaction mixture was filtered over Celite (P3) to obtain a clear solution. The solution was concentrated and left to crystallize at 5 °C to afford colorless crystals. Yield: 0.426 g (23 %); ¹H NMR (CDCl₃, 400 MHz): δ 8.61 (t, ⁴J_{H-H} = 2.2 Hz, 2H, ArH between two C-O moieties), 7.43 (d, ⁴J_{H-H} = 2.0 Hz, 4H, *o*-ArH), 3.90 (s, 6H, CO₂CH₃), 1.27 (s, 36H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 166.73 (s, C=O), 154.10 (s, O-ArC), 131.41 (s, C(O)-ArC), 117.59 (s, *m*-ArC), 113.89 (d, ³J_{P-C} = 9.1 Hz, ArC between the carbons bind to oxygen), 52.37 (CO₂CH₃), 52.12 (t, ²J_{P-C} = 11.1 Hz, C(CH₃)₃), 31.31 (t, ³J_{P-C} = 5.8 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 132.76 (s); m.p. 285 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1724 (C=O), 1593 (C=O); *m/z*: 741.25 [M+1]⁺;

Table 2.24. Crystal data and structure refinement for compound **5.5**.

Empirical Formula	C ₁₆ H ₂₄ N ₂ O ₄ P ₂	Volume (Å ³)	1933.4(2)
F _w	370.31 g/mol	Z	4
T (K)	103(2)	ρ _{calc} (g/cm ³)	1.272
λ (Å)	0.71073	μ, (mm ⁻¹)	0.246
Crystal System	Monoclinic	F(000)	784
Space Group	P 1 21/c 1	Crystal Size (mm)	0.060 x 0.120 x 0.140
Cell length (Å)	a = 9.2244(6)	2θ range (°)	2.97 to 29.71
	b = 11.6061(9)	Reflections collected	24987
	c = 18.1414(13)	Indep. Refl. (R _{int})	5450 [R(int) = 0.0869]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.496 and -0.449
	β = 95.473(3)	R1, wR2 (<i>I</i> > 2σ(<i>I</i>))	0.0530, 0.1122
	γ = 90	R1, wR2 (all data)	0.0953, 0.1304

2.5.6 - Synthesis of [(*(O)P(μ-N^tBu)*)₂(μ-3,5-C₆H₃O₂(CO₂Me))]₂ (**5.6**)

Compound **5.5** (0.148 g, 0.20 mmol) was dissolved in 10 mL toluene. *Tert*-butyl hydroperoxide (0.17 cm³, 1.21 mmol) was added dropwise at 0 °C and left to stir overnight. The reaction solvent was reduced to about 2 mL and 2 mL of THF was added. The solution was left to crystallize at -20 °C, however to date no pure crystals or solid has been obtained. ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ -12.36 (s);

2.5.7 - Synthesis of $[(\text{(S)P}(\mu\text{-N}^t\text{Bu}))_2(\mu\text{-3,5-C}_6\text{H}_3\text{O}_2(\text{CO}_2\text{Me}))]_2$ (**5.7**)

To a 10 mL toluene solution of **5.5** (0.148 g, 0.2 mmol), elemental sulfur (0.032 mg, 1.0 mmol) was added. The reaction mixture was brought to reflux and monitored by ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy. The unreacted sulfur was filtered and product was extracted repeatedly with THF and toluene. The filtrates were combined and evaporated to obtain solid. Crystals were obtained from recrystallization of the solid in benzene and chloroform. Yield: negligible, sufficient for spectroscopic analyses; ^1H NMR (C_6D_6 , 400 MHz): δ 8.26 (t, $^4J_{\text{H-H}} = 2.4$ Hz, 2H, ArH between two C-O moieties), 8.13 (d, $^4J_{\text{H-H}} = 2.0$ Hz, 4H, *o*-ArH), 3.32 (s, 6H, CO_2CH_3), 1.43 (s, 36H, $\text{C}(\text{CH}_3)_3$); ^{13}C NMR (CDCl_3 , 101 MHz): δ 165.15 (s, $\text{C}=\text{O}$), 151.56 (t, $^3J_{\text{P-C}} = 6.6$ Hz, O-ArC), 132.81 (s, C(O)-ArC), 118.95 (*o*-ArC), 116.52 (s, ArC between the carbons bind to oxygen), 57.85 (s, $\text{C}(\text{CH}_3)_3$), 52.94 (s, CO_2CH_3), 29.77 (t, $^3J_{\text{P-C}} = 4.5$ Hz, $\text{C}(\text{CH}_3)_3$); ^{31}P - $\{^1\text{H}\}$ NMR (C_6D_6 , 162 MHz): δ 40.51 (s); MS (EI) m/z : 869.14 $[\text{M}+1]^+$;

Table 2.25. Crystal data and structure refinement for compound **5.7**.

Empirical Formula	$\text{C}_{44}\text{H}_{60}\text{N}_4\text{O}_8\text{P}_4\text{S}_4$	Volume ($\text{\AA}^3$)	2507.19(13)
F_w	1025.08 g/mol	Z	2
T (K)	100(2)	ρ_{calc} (g/cm^3)	1.358
λ ($\text{\AA}$)	0.71073	μ , (mm^{-1})	0.371
Crystal System	Monoclinic	F(000)	1080
Space Group	P 1 21/c 1	Crystal Size (mm)	0.280 x 0.320 x 0.420
Cell length ($\text{\AA}$)	$a = 12.0333(4)$	2θ range ($^\circ$)	2.41 to 31.01

	b = 12.6498(3)	Reflections collected	45076
	c = 17.4441(6)	Indep. Refl. (R _{int})	7994 [R(int) = 0.0427]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.435 and -0.376
	β = 109.2284(11)	R1, wR2 (I > 2σ(I))	0.0327, 0.0768
	γ = 90	R1, wR2 (all data)	0.0422, 0.0820

2.5.8 - Synthesis of [((Se)P(μ-N^tBu))₂(μ-3,5-C₆H₃O₂(CO₂Me))]₂ (5.8)

Compound **5.8** was synthesized using similar procedure to that for **5.7**: **5.5** (0.096 g, 0.13 mmol) and elemental selenium (0.046 g, 0.58 mmol). Yield: 0.014 g (10 %); ¹H NMR (CDCl₃, 400 MHz): δ 8.01 (s, 2H, ArH between two C-O moieties), 7.90 (s, 4H, *o*-ArH), 3.94 (s, 6H, CO₂CH₃), 1.60 (s, 36H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 165.05 (s, C=O), 151.46 (d, ³J_{P-C} = 14.1 Hz, O-ArC), 132.65 (s, C(O)-ArC), 119.30 (*o*-ArC), 116.94 (s, ArC between the carbons bind to oxygen), 58.61 (s, CO₂CH₃), 52.96 (s, C(CH₃)₃), 29.83 (t, ³J_{P-C} = 4.0 Hz, C(CH₃)₃); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 32.95 (s, with satellite doublet ¹J_{P-Se} = 1003.0 Hz); m.p. 338 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1724 (C=O), 1589 (C=O), 903 (P=Se); MS (EI) *m/z*: 1060.92 [M+1]⁺;

2.5.9 - Synthesis of [(^tBuHN)P(μ-N^tBu)₂P]₂(μ-3,5-C₆H₃O₂(CO₂Me)) (5.9)

Compound **1.2** (1.872 g, 6.0 mmol) and triethylamine (0.84 cm³, 6.0 mmol) were dissolved in 40 mL THF. Methyl 3,5-dihydroxybenzoate (0.504 g, 3.0 mmol) in 30 mL

THF was added dropwise to the reaction mixture at room temperature. The reaction mixture was stirred overnight, and the resulting ammonium chloride was filtered off. The filtrate was evaporated to dryness and recrystallize in toluene at 5 °C to yield colorless crystals. Yield: 1.723 g (78 %); ^1H NMR (CDCl_3 , 400 MHz): δ 7.55 (d, $^4J_{\text{H-H}} = 2.4$ Hz, 2H, *o*-Ar**H**), 6.95 (t, $^4J_{\text{H-H}} = 2.0$ Hz, 1H, **H** between two hydroxyl groups), 3.89 (s, 3H, CO_2CH_3), 2.26 (d, $^2J_{\text{P-H}} = 8.4$ Hz, 2H, **NH**), 1.34 (s, 36H, $\text{C}(\text{CH}_3)_3$ on P_2N_2 rings), 1.08 (s, 18H, $\text{C}(\text{CH}_3)_3$ on side chain); ^{13}C NMR (CDCl_3 , 101 MHz): δ 166.71 (s, $\text{C}=\text{O}$), 153.30 (d, $^2J_{\text{P-C}} = 7.0$ Hz, ArC-O), 129.96 (s, ArC-C=O), 122.82 (s, ArC-C-C=O), 119.04 (d, $^3J_{\text{P-C}} = 4.0$ Hz, ArC between two carbonyl groups), 52.30 (t, $^2J_{\text{P-C}} = 7.1$ Hz, $\text{C}(\text{CH}_3)_3$ on the P_2N_2 rings), 52.11 (s, CO_2CH_3), 51.51 (d, $^2J_{\text{P-C}} = 14.1$ Hz, $\text{C}(\text{CH}_3)_3$ on side chain), 32.75 (d, $^3J_{\text{P-C}} = 9.1$ Hz, $\text{C}(\text{CH}_3)_3$ on side chain), 31.42 (t, $^3J_{\text{P-C}} = 6.6$ Hz, $\text{C}(\text{CH}_3)_3$ on P_2N_2 rings); ^{31}P - $\{^1\text{H}\}$ NMR (CDCl_3 , 162 MHz): δ 131.09 (d, $^2J_{\text{P-P}} = 9.7$ Hz, **P**-O), 101.55 (d, $^2J_{\text{P-P}} = 9.7$ Hz, **P**-N); m.p. 153 °C; IR (mineral oil, NaCl) ν (cm^{-1}): 3337 (N-H stretching), 1730 ($\text{C}=\text{O}$), 1585 (N-H bending); MS (EI) m/z : 719.38 $[\text{M}+1]^+$;

Table 2.26. Crystal data and structure refinement for compound 5.9.

Empirical Formula	$\text{C}_{32}\text{H}_{62}\text{N}_6\text{O}_4\text{P}_4$	Volume ($\text{\AA}^3$)	4054.7(5)
F_w	718.75 g/mol	Z	4
T (K)	103(2)	ρ_{calc} (g/cm^3)	1.177
λ ($\text{\AA}$)	0.71073	μ , (mm^{-1})	0.226
Crystal System	Monoclinic	F(000)	1552
Space Group	P 1 21/n 1	Crystal Size (mm)	0.220 x 0.290 x 0.300
Cell length ($\text{\AA}$)	a = 9.4506(8)	2 θ range ($^\circ$)	2.46 to 31.03
	b = 25.855(2)	Reflections collected	39162
	c = 16.6290(10)	Indep. Refl. (R_{int})	12815 [$R(\text{int}) = 0.0787$]
Cell angles ($^\circ$)	$\alpha = 90$	Larg. Diff. Peak & hole ($\text{e}\text{\AA}^{-3}$)	0.437 and -0.381
	$\beta = 93.717(3)$	R1, wR2 ($I > 2\sigma(I)$)	0.0589, 0.1254
	$\gamma = 90$	R1, wR2 (all data)	0.1059, 0.1453

2.5.10 - Synthesis of $[(^t\text{BuHN})(\text{O})\text{P}(\mu\text{-}^t\text{Bu})_2\text{P}(\text{O})]_2(\mu\text{-}3,5\text{-C}_6\text{H}_3\text{O}_2(\text{CO}_2\text{Me}))$ (**5.10**)

To a 10 mL THF solution of **5.9** (0.359 g, 0.5 mmol), *tert*-butyl hydroperoxide (0.28 cm³, 2.0 mmol) was added dropwise at room temperature. The reaction mixture was stirred overnight and THF was replaced with hexane and the ammonium salt was removed *via* filtration. The filtrate was left to crystallize at room temperature to afford crystalline solid. Yield: 0.035 g (9 %); ¹H NMR (CDCl₃, 400 MHz): δ 7.79 (d, ⁴J_{H-H} = 2.0 Hz, 2H, *o*-ArH), 7.67 (br s, 1H, H between two hydroxyl groups), 3.94 (s, 3H, CO₂CH₃), 2.48 (d, ²J_{P-H} = 8.0 Hz, 2H, N-H), 1.46 (s, 36H, C(CH₃)₃ on P₂N₂ rings), 1.43 (s, 18H, C(CH₃)₃ on side chain); ¹³C NMR (CDCl₃, 101 MHz): δ 165.58 (s, C=O), 152.32 (d, ²J_{P-C} = 4.0 Hz, ArC-O), 132.59 (s, ArC-C=O), 118.07 (s, ArC between two carbonyl groups), 55.71 (s, CO₂CH₃), 53.72 (s, C(CH₃)₃ on side chain), 52.82 (s, C(CH₃)₃ on P₂N₂ rings), 31.98 (d, ³J_{P-C} = 3.0 Hz, C(CH₃)₃ on side chain), 30.55 (t, ³J_{P-C} = 4.5 Hz, C(CH₃)₃ on P₂N₂ rings); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ -4.09 (s, P-O), -4.17 (s, P-N); MS (EI) *m/z*: 783.36 [M+1]⁺;

2.5.11 - Synthesis of $[(^t\text{BuHN})(\text{S})\text{P}(\mu\text{-}^t\text{Bu})_2\text{P}(\text{S})]_2(\mu\text{-}3,5\text{-C}_6\text{H}_3\text{O}_2(\text{CO}_2\text{Me}))$ (**5.11**)

To a 15 mL toluene solution of **5.9** (0.359 g, 0.5 mmol), elemental sulfur (0.096 g, 3.0 mmol) was added and the reaction mixture was heated to reflux for overnight. The reaction mixture gradually turned yellow. Toluene was removed under reduced pressure. The product was extracted with 3 x 20 mL hexane. The solution was concentrated and

left at 5 °C to yield yellow sulfur crystals in the first few batches. After repeated recrystallization and filtering off the crystalline sulfur, the hexane solution eventually yielded white crystalline solid at room temperature. Yield: 0.123 g (29 %); ^1H NMR (CDCl_3 , 400MHz): δ 7.71 (s, 2H, *o*-Ar**H**), 7.38 (s, 1H, **H** between two hydroxyl groups), 3.94 (s, 3H, CO_2CH_3), 3.18 (d, $^2J_{\text{P-H}} = 8.8$ Hz, 2H, N-**H**), 1.67 (s, 36H, $\text{C}(\text{CH}_3)_3$ on P_2N_2 rings), 1.47 (s, 18H, $\text{C}(\text{CH}_3)_3$ on side chain); ^{13}C NMR (CDCl_3 , 101 MHz): δ 165.50 (s, $\text{C}=\text{O}$), 151.81 (d, $^2J_{\text{P-C}} = 9.1$ Hz, Ar**C**-O), 131.91 (s, Ar**C**- $\text{C}=\text{O}$), 121.50 (t, $^3J_{\text{P-C}} = 4.5$ Hz, Ar**C** between two carbonyl groups), 119.86 (d, $^3J_{\text{P-C}} = 3.0$ Hz, Ar**C**- $\text{C}-\text{C}=\text{O}$), 57.88 (s, CO_2CH_3), 55.37 (d, $^2J_{\text{P-C}} = 6.1$ Hz, $\text{C}(\text{CH}_3)_3$ on side chain), 52.82 (s, $\text{C}(\text{CH}_3)_3$ on P_2N_2 rings), 31.55 (d, $^3J_{\text{P-C}} = 4.0$ Hz, $\text{C}(\text{CH}_3)_3$ on side chain), 30.00 (t, $^3J_{\text{P-C}} = 4.0$ Hz, $\text{C}(\text{CH}_3)_3$ on P_2N_2 rings); ^{31}P - $\{^1\text{H}\}$ NMR (CDCl_3 , 162 MHz): δ 48.39 (d, $^2J_{\text{P-P}} = 29.2$ Hz, **P**-O), 39.68 (d, $^2J_{\text{P-P}} = 29.2$ Hz, **P**-N); MS (EI) m/z : 847.27 $[\text{M}+1]^+$;

Table 2.27. Crystal data and structure refinement for compound 5.11.

Empirical Formula	$\text{C}_{71}\text{H}_{132}\text{N}_{12}\text{O}_8\text{P}_8\text{S}_8$	Volume ($\text{\AA}^3$)	5225.5(10)
F_w	1786.12 g/mol	Z	2
T (K)	103(2)	ρ_{calc} (g/cm^3)	1.135
λ ($\text{\AA}$)	0.71073	μ , (mm^{-1})	0.342
Crystal System	Monoclinic	F(000)	1908
Space Group	P 1 21/n 1	Crystal Size (mm)	0.200 x 0.320 x 0.400
Cell length ($\text{\AA}$)	$a = 14.0707(14)$	2θ range ($^\circ$)	1.68 to 28.00
	$b = 15.2769(17)$	Reflections collected	71619
	$c = 25.224(3)$	Indep. Refl. (R_{int})	12617 [$R_{\text{int}} = 0.1169$]
Cell angles ($^\circ$)	$\alpha = 90$	Larg. Diff. Peak & hole ($\text{e}\text{\AA}^{-3}$)	0.941 and -0.466
	$\beta = 105.476(3)$	R_1 , wR_2 ($I > 2\sigma(I)$)	0.0871, 0.2429
	$\gamma = 90$	R_1 , wR_2 (all data)	0.1838, 0.3246

2.5.12 - Synthesis of $[(^t\text{BuHN})(\text{Se})\text{P}(\mu\text{-}^t\text{NBu})_2\text{P}(\text{Se})]_2(\mu\text{-}3,5\text{-C}_6\text{H}_3\text{O}_2(\text{CO}_2\text{Me}))$ (**5.12**)

Compound **5.12** was synthesized *via* similar procedure to that of **5.11** by reacting **5.9** (0.718 g, 1.0 mmol) with elemental selenium (0.395 g, 5.0 mmol). Crystals were recrystallized in toluene. Yield: 0.614 g (59 %); ^1H NMR (CDCl_3 , 400 MHz): δ 7.69 (d, $^4J_{\text{H-H}} = 1.6$ Hz, 2H, *o*-ArH), 7.38 (t, $^4J_{\text{H-H}} = 2.0$ Hz, 1H, H between two hydroxyl groups), 3.93 (s, 3H, CO_2CH_3), 3.56 (d, $^2J_{\text{P-H}} = 13.2$ Hz, 2H, N-H), 1.74 (s, 36H, $\text{C}(\text{CH}_3)_3$ on P_2N_2 rings), 1.51 (s, 18H, $\text{C}(\text{CH}_3)_3$ on side chain); ^{13}C NMR (CDCl_3 , 101 MHz): δ 165.47 (s, C=O), 151.69 (d, $^2J_{\text{P-C}} = 10.1$ Hz, ArC-O), 131.87 (s, ArC-C=O), 122.09 (s, ArC-C-C=O), 120.34 (s, ArC between two carbonyl groups), 58.80 (s, CO_2CH_3), 56.78 (d, $^2J_{\text{P-C}} = 9.1$ Hz, $\text{C}(\text{CH}_3)_3$ on side chain), 52.86 (s, $\text{C}(\text{CH}_3)_3$ on P_2N_2 rings), 31.64 (d, $^3J_{\text{P-C}} = 4.0$ Hz, $\text{C}(\text{CH}_3)_3$ on side chain), 30.02 (t, $^3J_{\text{P-C}} = 4.0$ Hz, $\text{C}(\text{CH}_3)_3$ on P_2N_2 rings); $^{31}\text{P}\{-^1\text{H}\}$ NMR (CDCl_3 , 162 MHz): δ 42.05 (d, $^2J_{\text{P-P}} = 13.0$ Hz, with satellite doublets of doublets with coupling constant of $^1J_{\text{P-Se}} = 967.1$ Hz, P-O), 26.73 (d, $^2J_{\text{P-P}} = 13.0$ Hz, with satellite doublets of doublets with coupling constant of $^1J_{\text{P-Se}} = 884.5$ Hz, P-N);

Table 2.28. Crystal data and structure refinement for compound **5.12**.

Empirical Formula	$\text{C}_{85}\text{H}_{148}\text{N}_{12}\text{O}_8\text{P}_8\text{Se}_8$	Volume ($\text{\AA}^3$)	5310.3(9)
F_w	2344.66 g/mol	Z	2
T (K)	103(2)	ρ_{calc} (g/cm^3)	1.467
λ ($\text{\AA}$)	0.71073	μ , (mm^{-1})	2.927
Crystal System	Monoclinic	F(000)	2396
Space Group	P 1 21/c 1	Crystal Size (mm)	0.360 x 0.400 x 0.420
Cell length ($\text{\AA}$)	a = 23.829(3)	2θ range ($^\circ$)	2.25 to 28.00
	b = 9.4169(9)	Reflections collected	87457

	$c = 25.684(3)$	Indep. Refl. (R_{int})	12814 [$R(\text{int}) = 0.1070$]
Cell angles ($^{\circ}$)	$\alpha = 90$	Larg. Diff. Peak & hole ($\text{e}\text{\AA}^{-3}$)	0.953 and -0.897
	$\beta = 112.8702(19)$	$R1, wR2$ ($I > 2\sigma(I)$)	0.0483, 0.0923
	$\gamma = 90$	$R1, wR2$ (all data)	0.0757, 0.1011

2.6 - Syntheses of new compounds in Chapter 6

2.6.1 - Synthesis of $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}]_3(\mu\text{-1,3,5-C}_6\text{H}_3\text{O}_3)$ (**6.1**)

To a 20 mL THF solution of phloroglucinol (0.126 g, 1.0 mmol) and triethylamine (0.42 cm³, 3.0 mmol), compound **1.2** (0.933 g, 3.0 mmol) in 20 mL THF was added dropwise at room temperature and left to stir overnight. The reaction solvent was evaporated under reduced pressure and product was extracted with hexane. The hexane filtrate was then dried to afford white solid. Yield: 0.352 g (37 %); ¹H NMR (CDCl₃, 400 MHz): δ 6.55 (s, 3H, ArH), 2.90 (br s, 3H, N-H), 1.32 (s, 54H, C(CH₃)₃), 1.21 (s, 27H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 154.14 (s, ArC-O), 110.97 (s, *o*-ArC), 52.02 (t, ²*J*_{P-C} = 10.4 Hz, C(CH₃)₃ of P₂N₂ rings), 51.63 (d, ²*J*_{P-C} = 13.6 Hz, C(CH₃)₃ on the side chain), 33.00 (d, ³*J*_{P-C} = 9.0 Hz, C(CH₃)₃ on the side chain), 31.54 (t, ³*J*_{P-C} = 6.5 Hz, C(CH₃)₃ of P₂N₂ rings); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 137.20 (s, P-O), 105.08 (s, P-N);

2.6.2 - Synthesis of $[(^t\text{BuHN})(\text{S})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{S})]_3(\mu\text{-1,3,5-C}_6\text{H}_3\text{O}_3)$ (**6.3**)

To a 20 mL THF solution of phloroglucinol (0.126 g, 1.0 mmol) and triethylamine (0.42 cm³, 3.0 mmol), **1.2** (0.933 g, 3.0 mmol) in 20 mL THF was added dropwise at room temperature and left to stir overnight. After which, elemental sulfur (0.192 g, 6.0 mmol) was added and the reaction mixture was further stirred for overnight. The reaction mixture was filtered to remove triethylammonium chloride and unreacted sulfur. The filtrate was evaporated and further washed with hexane. The resulting solid was then dissolved in ethyl acetate and left at room temperature to afford pure solid of **6.3**. Yield: 0.217 g (19 %); ¹H NMR (C₆D₆, 400 MHz): δ 7.40 (d, ⁴J_{P-H} = 1.6 Hz, 3H, Ar**H**), 3.11 (d, ²J_{P-H} = 10.0 Hz, 3H, N-**H**), 1.72 (s, 54H, C(**CH**₃)₃), 1.21 (s, 27H, C(**CH**₃)₃); ¹³C NMR (C₆D₆, 101 MHz): δ 152.41 (s, ArC-O), 114.02 (s, ArC), 57.99 (s, C(**CH**₃)₃ on P₂N₂ rings), 55.01 (d, ²J_{P-C} = 7.1 Hz, C(**CH**₃)₃ on sidechain), 31.35 (d, ³J_{P-C} = 4.0 Hz, C(**CH**₃)₃ on the side chain), 30.16 (t, ³J_{P-C} = 4.5 Hz, C(**CH**₃)₃ of P₂N₂ rings); ³¹P-{¹H} NMR (C₆D₆, 162 MHz): δ 48.27 (d, ²J_{P-P} = 29.2 Hz, **P**-N), 39.39 (d, ²J_{P-P} = 29.2 Hz, **P**-O); MS (EI) *m/z*: 1144.36 [M+1]⁺;

2.6.3 - Synthesis of $[(^t\text{BuHN})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{Se})]_3(\mu\text{-1,3,5-C}_6\text{H}_3\text{O}_3)$ (**6.4**)

Identical to synthetic procedure of **6.3**, **1.2** (0.933 g, 3.0 mmol), phloroglucinol (0.126 g, 1.0 mmol), triethylamine (0.42 cm³, 3.0 mmol), and elemental selenium (0.474 g, 6.0 mmol) was used. The reaction mixture was filtered to remove triethylammonium chloride and unreacted selenium. The filtrate was evaporated to dryness and chloroform was added to recrystallize the product at room temperature, yielding needle-like crystals. Yield: 0.898 g (63 %); ¹H NMR (CDCl₃, 400 MHz): δ 6.97 (s, 3H, ArH), 3.06 (d, ²J_{P-H} = 14.0 Hz, 3H, N-H), 1.72 (s, 54H, C(CH₃)₃), 1.50 (s, 27H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 151.54 (s, ArC-O), 114.22 (s, ArC), 58.73 (s, C(CH₃)₃ on P₂N₂ rings), 56.77 (d, ²J_{P-C} = 10.1 Hz, C(CH₃)₃ on sidechain), 31.65 (d, ³J_{P-C} = 4.5 Hz, C(CH₃)₃ on the side chain), 30.01 (t, ³J_{P-C} = 4.5 Hz, C(CH₃)₃ of P₂N₂ rings); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 41.64 (d, ²J_{P-P} = 13.0 Hz, ¹J_{P-Se} = 967.1 Hz, P-N), 26.72 (d, ²J_{P-P} = 13.0 Hz, ¹J_{P-Se} = 884.5 Hz, P-O); m.p. 216 °C; IR (mineral oil, NaCl) ν (cm⁻¹): 1647 (N-H bend), 1628 (N-H bend), 1597 (N-H bend), 895 (P=Se); MS (EI) *m/z*: 1432.04 [M+1]⁺;

Table 2.29. Crystal data and structure refinement for compound **6.4**.

Empirical Formula	C ₄₂ H ₈₇ N ₉ O ₃ P ₆ Se ₆	Volume (Å ³)	6226.7(2)
F _w	1425.78 g/mol	Z	4
T (K)	100(2)	ρ _{calc} (g/cm ³)	1.521
λ (Å)	0.71073	μ, (mm ⁻¹)	3.721
Crystal System	Orthorhombic	F(000)	2880
Space Group	P 21 21 21	Crystal Size (mm)	0.040 x 0.080 x 0.100

Cell length (Å)	a = 15.1418(3)	2θ range (°)	2.42 to 26.39
	b = 15.1535(3)	Reflections collected	86112
	c = 27.1375(6)	Indep. Refl. (R _{int})	12727[R(int) = 0.0885]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.753 and -0.423
	β = 90	R1, wR2 (I>2σ(I))	0.0361, 0.0822
	γ = 90	R1, wR2 (all data)	0.0467, 0.0866

2.6.4 - Synthesis of [tBuHN(P(μ-N^tBu)₂P)]₂[(μ-1,3,5-C₆H₃O₃)(P(μ-N^tBu)₂P)]₂ (**6.5**)

To a 20 mL THF solution of phloroglucinol (0.126 g, 1.0 mmol) and triethylamine (0.42 cm³, 3.0 mmol), **1.1** (0.275 g, 1.0 mmol) and **1.2** (0.311 g, 1.0 mmol) were dissolved in 40 mL THF and added dropwise at -78 °C. The resulting mixture was gradually warmed up to room temperature and stirred overnight. The mixture was filtered to remove triethylammonium chloride. The filtrate was evaporated under reduced pressure and recrystallized in hexane to yield needle-like crystals. Yield: 0.320 g (53 %); ¹H NMR (CDCl₃, 400 MHz): δ 8.06 (s, 2H, ArH), 6.49 (s, 4H, ArH), 1.35 (s, 36H, C(CH₃)₃), 1.24 (s, 36H, C(CH₃)₃), 1.13 (s, 18H, C(CH₃)₃); ¹³C NMR (CDCl₃, 101 MHz): δ 153.86 (d, ²J_{P-C} = 5.1 Hz, ArC-O), 108.52 (s, o-ArC), 107.88 (s, o-ArC), 52.32-51.88 (m, overlap of C(CH₃)₃), 32.91 (d, ³J_{P-C} = 9.1 Hz, C(CH₃)₃ on the side chain), 31.52-31.31 (m, overlap of C(CH₃)₃ of P₂N₂ rings); ³¹P-{¹H} NMR (CDCl₃, 162 MHz): δ 132.04 (br s, P-O), 102.41 (s, P-N); MS (EI) m/z: 1207.56 [M+1]⁺;

Table 2.30. Crystal data and structure refinement for compound **6.5**.

Empirical Formula	C ₅₂ H ₉₈ N ₁₀ O ₆ P ₈	Volume (Å ³)	3380.39(10)
F _w	1207.16 g/mol	Z	2
T (K)	173(2)	ρ _{calc} (g/cm ³)	1.186
λ (Å)	1.54178	μ, (mm ⁻¹)	2.327
Crystal System	Monoclinic	F(000)	1296
Space Group	P 1 21/c 1	Crystal Size (mm)	0.040 x 0.060 x 0.120
Cell length (Å)	a = 9.8340(2)	2θ range (°)	4.50 to 66.65
	b = 18.0678(3)	Reflections collected	17931
	c = 19.0600(3)	Indep. Refl. (R _{int})	5822 [R(int) = 0.0885]
Cell angles (°)	α = 90	Larg. Diff. Peak & hole (eÅ ⁻³)	0.742 and -0.738
	β = 93.4596(15)	R1, wR2 (I>2σ(I))	0.0768, 0.2204
	γ = 90	R1, wR2 (all data)	0.1036, 0.2547

Chapter 3 – Synthesis of Cyclophosphazanes *via* Mechanochemistry

3.1 - Introduction to Mechanochemistry

To date, chemical transformations involving cyclodiphosphazanes are generally performed in solution, at times under refluxing conditions. In this thesis, we refer to traditional synthetic methods as solution-based batch processes. In general, the solvent choice in these processes plays a crucial role in determining whether the desired chemical transformation take place, to what extent and at what rate it does so. Beside that, the solubility of the reactants must be accounted when choosing the appropriate reaction solvent. It is for most part due to the heavy dependency on such solvents – be it for the synthesis, isolation, purification or characterisation of the desired products – that these wet methods are considered as inherently inefficient.¹²⁷ In our group, the concern regarding the solvent choice has been surfacing over the past years, especially in cyclodiphosph(III)azane projects. Particularly, when the nucleophile of interest is only soluble in protic solvents (*e.g.*, MeOH or IPA), yet these solvents are incompatible with dichlorocyclodiphosph(III)azanes. Hence, it is of utmost importance to explore more efficient synthetic alternatives to address the solubility issue encountered.

Solid-state approaches, such as mechanochemical methods, are rapidly emerging as an excellent solvent-free and atom-efficient synthetic alternative to the traditional solution-based methods.^{128–135} Mechanochemistry refers to chemical transformations that are induced by mechanical forces generated by typical methods such as shearing, friction, grinding or compressions.^{136,137} Some domains of mechanochemistry include sonochemical transformations, tribochemistry, atomic force microscope (AFM) induced bond scissions, and the more commonly utilized, mortar and pestle grinding and ball milling for chemical synthesis.¹³⁸ With regards to the context and discussion in this thesis, “mechanochemical synthetic method” will be limited to solid-state reactivity induced by mechanochemical ball milling techniques. This mechanochemical synthetic

approach is rapidly gaining popularity in the areas of organic synthesis,^{139–143} supramolecular chemistry, catalysis and synthesis of metal-organic framework (MOF) materials.^{144–148} However, the use of mechanochemistry within the field of organometallic and main group chemistry are still in its infancy.

In this section, some seminal examples highlighting the use of ball milling in synthesis of organometallic compounds will be discussed. As most of the examples are relevant and pertain to main group chemistry, which is the focus of this thesis, they will illustrate the concept and benefits of mechanochemistry.

Scheme 3.1. Two-steps mechanochemical oxidation via (i) and (ii), or one-pot one-step, to obtain $[\text{Re}(\text{CO})_3\text{Br}_3][\text{TEA}]_2$.¹⁴⁹

The solution-based oxidations of zerovalent metal carbonyls to pentacarbonylmethyl(I)-halides, $\text{M}(\text{CO})_5\text{X}$ ($\text{M} = \text{Re}, \text{Mn}$ and $\text{X} = \text{Cl}, \text{Br}$ or I), are well-established, albeit relatively poor yields and conversions.¹⁴⁹ As a proof-of-concept study, Friščić and co-workers investigated the use of mechanochemistry to improve reactivity of the reactants and achieve higher yields of the desired products.^{150,151} It was reported that milling the metal hexacarbonyls ($\text{M}(\text{CO})_6$) with appropriate sodium halides (NaX) in the presence of oxone (*i.e.* potassium peroxomonosulfate), resulted in complete oxidation to the corresponding pentacarbonylmethyl(I) halides in 5 minutes. As the study aimed to demonstrate the potential of multi-component ball milling to access *fac*-tricarbonyl metal complexes, the team hence further milled the *in situ* generated $\text{Re}(\text{CO})_5\text{Br}$ with tetraethylammonium bromide (TEAB) and led to formation of $[\text{Re}(\text{CO})_3\text{Br}_3][\text{TEA}]_2$

(Scheme 3.1). They then also demonstrated that the latter compound can be readily synthesized *via* mechanochemical milling of rhenium(I) hexacarbonyl, TEAB and oxone in a “one-step multi-component” manner.

Scheme 3.2. Formation of Cu(I)-NHC complexes via mechanochemical synthetic method.¹⁵²

Another example of mechanochemical synthesis is the preparation of organometallic complexes, (NHC)CuCl, as reported by Lamaty and co-workers. The Cu(I)-NHC complexes have been commonly prepared by reacting imidazolium precursors with a strong base, followed by reaction with Cu(I). A less frequently used solution-based approach is to react imidazolium salt directly with metallic Cu(0). However, this approach is compounded by several problems, such as the poor solubility of the Cu(0) which requires large excess of the metal and long reaction times. Lamaty and co-workers therefore proposed to replace the solution-based method with mechanochemical ball milling to evaluate the chemical transformation between imidazolium salts and metallic Cu(0). They demonstrated that the addition of water (0.3 $\mu\text{L}/\text{mg}$ of reactants) assisted in the conversion of IMes·HCl to the corresponding Cu(I)-NHC complex after milling for 8 hours at 450 rpm without the need of excess Cu(0). Alternatively, they also conducted the reactions in air or under oxygen-filled environment in absence of water additive, illustrating the need for O₂ as an oxidant to oxidize Cu(0) to Cu(I) (Scheme 3.2).¹⁵² This report serves to demonstrate the compatibility of mechanochemistry in conducting reactions that involve liquid, solid and gaseous substrates to create value-added products.¹⁵²

Scheme 3.3. Mechanochemical synthesis of bis(*n*-propyltetramethylcyclopentadienyl)strontium.¹⁵³

Apart from being widely used in transition metal chemistry, mechanochemistry remains largely unexplored within the main group arena, with only a handful of reported examples.^{153–156} One such example is the synthesis of bis(*n*-propyltetramethylcyclopentadienyl)strontium, SrCp'_2 . The complex was previously obtained in only small quantities *via* solution-based salt metathesis reaction. The low yield was likely attributed to the poor solubility of reactants in reaction solvent (*i.e.* ether) which disfavours the salt metathesis reaction from proceeding. However, Peters and co-workers adapted the well-reported mechanochemical technique - liquid-assisted grinding (LAG) which introduce small amounts of liquid as an additive in the reaction¹⁵⁷ - and successfully performed upscaled reaction to synthesize SrCp'_2 .¹⁵³ Thus mechanochemistry, specifically LAG, has effectively provided a higher-yielding route for the synthesis of the strontium complex.

Scheme 3.4. Mechanochemical synthesis of tris(allyl)metal complexes.^{154–156}

On the other hand, Hanusa *et al.* also reported on their use of mechanochemistry in syntheses of main-group compounds, specifically tris(allyl)metal complexes. For instance, the solution-based syntheses of tris(allyl)aluminium complexes have typically resulted in formation of corresponding adducts with either the solvent used (THF) or,

the stronger base used to replace THF (*e.g.*, triphenylphosphine oxide (O=PPh₃) or pyridine). Whereas, in the case of ball milling, the reactions between aluminium trihalide (AlX₃) and three equivalents of KA' (A' = 1,3-(SiMe₃)₂C₃H₃) resulted in the first successful formations of coordinatively unsaturated tris(allyl)aluminum complexes (*Scheme 3.4*).¹⁵⁵

*Scheme 3.5. Synthesis of organogermanes from germanium (Ge) or germanium oxide (GeO₂); NMI = N-methylimidazole.*¹⁵⁸

Within the main group arena, organogermanes, GeR₄, are traditionally prepared from germanium tetrachloride, GeCl₄. Like many metal halides, GeCl₄ is a moisture-sensitive and corrosive liquid that readily hydrolyzes to germanium oxide and HCl in presence of water. Its intrinsic moisture-sensitivity often hinders their subsequent functionalization, resulting in poor yields under standard reaction conditions. Furthermore, large scale mineral processing of germanium ores typically requires harsh conditions, such as high temperatures and the use of large amounts of strong corrosive acids. Therefore, industrial manufacturing of GeCl₄ precursors and other germanium compounds can create a large ecological foot-print and is considered non-sustainable. Upon identifying these issues, Lumb, Friščić and co-workers, designed and successfully conducted mechanochemical synthesis of bench stable germanium catecholate complexes as

alternative for GeCl_4 (Scheme 3.5).¹⁵⁸ Subsequently, these germanium complexes were reacted with Grignard reagents to produce their corresponding highly pure organogermanes in high yields (Scheme 3.5).¹⁵⁸

Recently, our group also contributed our effort in promoting the use of solvent-free mechanochemistry in the syntheses of main group compounds.

Scheme 3.6. One-pot multi-step mechanochemical synthesis of indium(III)-BIAN complexes.¹⁵⁹

An example of our group's work is the syntheses of indium(III)-BIAN complexes (BIAN = Bis(arylimino)acenaphthene). Traditionally, the ligand – BIAN – is prepared by metal-templating method and hence demetallation step is essential to furnish the free ligand before complexation to other metal centers.^{160,161} Aligned with the increasing interest in developing 'greener' synthetic method with less solvent, higher yields and shorter reaction times, we hence proposed to evaluate the feasibility of mechanochemistry for the synthesis of BIAN ligands. It was demonstrated the ball milling of acenaphthoquinone with aniline in presence of 25 mol% of appropriate acid catalyst successfully resulted in the formation of corresponding BIAN ligands in high yields.¹⁵⁹ With that, we proceeded to extend the mechanochemical ball milling

technique to generate indium(III)-BIAN complexes *via* ‘one-pot two-step’ approach, effectively eliminating the need for demetallation and isolation of free ligand prior to addition of InCl_3 (Scheme 3.6).¹⁵⁹

Encouraged by these positive examples of mechanochemical ball milling reactions, our group employed this synthetic alternative to cyclodiphosphazane chemistry as well.

Scheme 3.7. Adamantoid phosphazane frameworks accessible by mechanochemistry.¹²

We have identified a specific chemical transformation reaction involving the ‘double-decked’ cyclodiphosphazane cages, $[\text{P}(\mu\text{-NR})_2\text{P}(\mu\text{-NR})]_2$. The accounts of neat heating of these cages were reported by Wolmerhäuser *et al.* and Chivers *et al.* on separate occasions. It was demonstrated that the isodemic isomerization of *iso*-propyl derivative to its more stable adamantoid structure can be achieved by heating at 156 °C for 12 days, while the *tert*-butyl analog was observed to be unaffected despite prolonged heating at 150 °C for 24 days.^{11,63} Since mechanochemistry has demonstrated to enable formation of previously inaccessible compounds,^{162,163} and hence our group attempted the rearrangement reactions of ‘double-decked’ cyclodiphosphazane-based cages in mechanochemical ball milling method.¹² We screened through various conditions and succeeded in generating the desired adamantoid by milling $[\text{P}(\mu\text{-N}^i\text{Pr})_2\text{P}(\mu\text{-N}^i\text{Pr})]_2$ with a salt additive (LiCl, 20 % wt) for 1.5 hours at 30 Hz (Scheme 3.7). This result was in stark contrast with the prolonged heating of 12 days at 156 °C reported previously. Taking it one step further, an analogous reaction involving the *tert*-butyl derivative (*i.e.* $[\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\mu\text{-N}^t\text{Bu})]_2$) was attempted. To our delight, the mechanochemical ball

milling successfully enabled the formation of previously inaccessible adamantoid isomer of $[P(\mu\text{-N}^t\text{Bu})_2P(\mu\text{-N}^t\text{Bu})]_2$ in high yields.¹²

3.2 - Nucleophilic substitution *via* mechanochemistry

3.2.1 – Prior work on syntheses of acyclic disubstituted cyclodiphosphazanes

Figure 3.1. Examples of acyclic disubstituted cyclodiphosphazanes where P-Cl bonds were replaced by newly formed P-N, P-O and P-C bonds respectively.^{13,16–18,164}

Dichlorocyclodiphosphazanes, $[ClP(\mu\text{-NR})]_2$, bearing reactive P-Cl moieties are used as starting material to generate more complex cyclodiphosphazane frameworks. The chemical modification on these dichlorocyclodiphosphazanes is generally performed *via* nucleophilic substitution reactions to form new P-N, P-O, P-C or P-S bonds. Some examples of such disubstituted compounds are shown in Fig. 3.1.^{13,16–18,164}

Scheme 3.8. Various synthetic strategies to form acyclic disubstituted acyclic cyclodiphosphazanes.^{13,165}

These nucleophilic substitutions can be carried out with the use of amine, alcohols, thiols or stronger nucleophiles such as lithiated amine and alcohols *etc* (Scheme 3.8).^{13,165} However, in some occasions, the solvent may hinder the reaction from proceeding when the required solvent is incompatible with dichlorocyclodiphosphazanes. Another potential problem is the low solubility of some nucleophiles in the reaction solvent used. While the latter can usually be alleviated by reflux, it typically lengthens the reaction time needed.

Scheme 3.9. Acyclic disubstituted cyclodiphosphazanes reported previously by mechanochemical synthetic method.¹⁶⁶

As mentioned earlier on, mechanochemistry can serve as an alternative synthetic method for reactions in which the solubility of the starting material(s) is an issue. Recently, our group reported on the feasible mechanochemical syntheses of cyclodiphosph(III)azane-based frameworks - demonstrating a few simple nucleophilic substitution reactions involving compound **1.1** - of which the organic nucleophiles are found to be only sparingly soluble in solvents that are compatible to **1.1** (Scheme 3.9).¹⁶⁶ Comparing to traditional solution-based method, such mechanochemical synthetic method significantly reduced the amount of solvents used in the entire synthetic processes, including the workup and purification step.

3.2.2 - Results and discussion for syntheses of new disubstituted cyclodiphosph(III)azanes (3.1 – 3.5)

Scheme 3.10. Formation of new acyclic disubstituted cyclodiphosph(III)azanes via mechanochemical ball milling.

Adding to our previously reported examples, we have further expanded the scope to generate more derivatives with the use of ball milling. In this study, four organic reactants (*i.e.* 1-adamantanol, 1-adamantylamine, *p*-aminobenzonitrile and mesitylamine) were used. The nucleophilic substitution reactions were conducted by loading compound **1.1**, the appropriate organic reactants and triethylamine in 1:2:2 molar ratio into the 10 mL stainless steel milling jars, charged with a 10 mm diameter 4 g stainless steel ball, under inert argon atmosphere (Scheme 3.10). These jars were then placed in a shaker mill and milled for a period of 3.5 to 4.0 hours at 30 Hz. All reactions performed have resulted in exclusive formation of one product as evident from the presence of only one singlet resonance signals on the *ex situ* ³¹P-{¹H} NMR spectra. Compounds **3.1** – **3.4** were successfully isolated with crystalline yields of 15 - 59 %.

Scheme 3.11. Expected and experimental results for the reaction of compound **1.1** with adenine.

On the other hand, the reaction of compound **1.1** with two equivalents of adenine led to cyclic product (**3.5**) being formed after milling for 4.0 hours at 30 Hz (*Scheme 3.11*). The *ex situ* ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy recorded showed two sets of doublets resonance signals, suggestive of completed conversion of **1.1**. It was initially predicted that bigger cyclic compound (**3.5'**) would be obtained. However, upon SC-XRD study of the isolated single crystals from the reaction mixture, compound **3.5** was obtained instead. It has been known that adenine exists in several tautomeric forms. The possible tautomeric forms of adenine can help to explain the formation of compound **3.5** - shift of N-H proton from position 9 to position 7 (Labelled structure of **3.5** in *Scheme 3.11*).¹⁶⁷

All these mechanochemical ball milling reactions were completed within 3.5 – 4.0 hours. The results obtained were similar to that achieved by solution-based overnight stirring methodology. All the compounds (**3.1** – **3.5**) were characterized by multinuclear NMRs, Fourier Transform Infra-red (FTIR) and single crystal X-ray diffraction (SC-XRD). The ^1H NMR spectra of compounds **3.1** and **3.2** showed singlet resonance signals at δ 2.12, 2.08, 1.62 and 1.35 ppm and, δ 2.03, 1.84, 1.63 and 1.30 ppm with the intensity of 1:2:2:3, which correspond to the adamantyl and *tert*-butyl groups. For compounds **3.3** and **3.4**, the resonance signals recorded were consistent with those of *para*-substituted aromatic ring and mesityl substituents respectively. The ^1H NMR spectrum of **3.5** exhibited resonance signals at δ 8.78, 8.38, 7.19 and 1.07 ppm with the intensity of 1:1:1:18, which was inconclusive as to whether the product obtained was **3.5** or **3.5'**. The structure was later confirmed by SC-XRD to be the monomeric cyclic product (**3.5**).

In addition, FTIR spectroscopy can also be used to monitor the reaction. The spectrum of **3.1** indicated the absence of O-H stretching bands, which suggested that the reaction was completed. While that of **3.2** - **3.4** displayed presence of secondary N-H stretching

at $\nu = 3333$, 3173 and 3323 cm^{-1} , respectively. The nitrile group present in **3.3** was further supported by the IR stretch at $\nu = 2212\text{ cm}^{-1}$ recorded.

3.2.3 - X-ray crystallographic studies of compounds **3.1** – **3.5**

Despite multiple attempts made, only diffraction quality single crystals of compounds **3.4** and **3.5** were obtained to date. In the cases of compounds **3.1** – **3.3**, partially hydrolyzed compounds have been isolated, further highlighting the innate sensitivity of these cyclodiphosph(III)azanes towards air and moisture.

Figure 3.2. ORTEP drawing of the molecular structure of compound **3.4** (left) and **3.5** (right). Thermal ellipsoids with 50 % probability at 103 and 100 K, respectively. **3.4**: Hydrogen atoms are omitted for clarity. Selected bond lengths (Å): P1-N1 1.7383(12), P1-N2 1.7269(12), P2-N1 1.7382(12), P2-N2 1.7279(12), P1-N3 1.6990(12), P2-N4 1.6953(12); Selected bond angles (°): N1-P1-N2 82.13(6), N1-P2-N2 82.11(6), N3-P1-N1 106.21(6), N3-P1-N2 99.86(6), P1-N1-P2 95.53(6), P1-N2-P2 96.70(6); **3.5**: Hydrogen atoms except proton H7, solvate molecule and another two independent molecules are omitted for clarity. Selected bond lengths (Å): P1-N1 1.74(2), P1-N2 1.713(2), P2-N1 1.688(2), P2-N2 1.694(2), P1-N7 1.706(2), P2-N3 1.787(2); Selected bond angles (°): N1-P1-N2 80.85(11), N1-P2-N2 82.45(12), N1-P1-N7 102.67(11), N1-P2-N3 98.51(11), P1-N1-P2 97.86(12), P1-N2-P2 98.07(12).

Compound **3.4** was recrystallized at room temperature from the filtered toluene solution of the reaction mixture. The SC-XRD analysis revealed the aromatic rings in **3.4** were almost co-planar to one another and slipped-stacked π - π interactions were observed between aromatic rings of one P_2N_2 molecule and aromatic rings of an adjacent P_2N_2 molecule (Fig. 3.2).

The SC-XRD analysis shed light for the reaction of compound **1.1** with two equivalents of adenine, which confirmed the formation of monomeric cyclic cyclodiphosphazane product (**3.5**) instead of the predicted dimeric species **3.5'**. It was observed that an

additional equivalent of adenine was necessary for the formation of single crystals as the solid-state structure revealed to be 1:1 cocrystal of compound **3.5** with adenine.

Figure 3.3. Illustration for the extensive hydrogen-bond interactions in the crystal structure of compound **3.5**. THF solvate molecules are omitted for clarity.

It is worth further discussing the molecular assembly of the single crystals of **3.5**. It was observed that cyclodiphosphazane **3.5** contains available hydrogen-bond acceptor and donor sites for intermolecular hydrogen-bond interactions. As illustrated in *Fig. 3.3*, these hydrogen-bond acceptor and donor sites have allowed hydrogen-bonding interactions to take place between the molecules of the cyclodiphosphazanes and adenine. The extensive hydrogen-bond interaction could be seen spanning across six cyclodiphosphazane molecules and two adenine molecules (indicated by red and blue coded molecules in *Fig. 3.3*). This therefore suggested the potential of utilizing compound **3.5** as a building block to create hybrid inorganic-organic supramolecular systems.

The endocyclic P-N bond distances in both **3.4** and **3.5** were comparable to the typical range of endocyclic P-N bond distances measured in structural analogs (1.727(1) - 1.738(1) Å and 1.688(2) – 1.74(2) Å, respectively *cf.* [(*o*-NH(^{*t*}Bu)C₆H₄)P(μ -N^{*t*}Bu)]₂: 1.707(3) – 1.728(3) Å and [(PhHN)P(μ -N^{*t*}Bu)]₂: 1.723(2) – 1.730(2) Å).^{18,164} The mean

exocyclic P-N bond distance in **3.4** was calculated to be 1.697(1) Å which was in good agreement with the typical exocyclic P-N bond distances reported in related analog, [(2,5-NH(*t*Bu)₂C₆H₃)P(μ -N^{*t*}Bu)]₂ (1.695(2) Å).¹⁸ On the other hand, the exocyclic P-N bond distances for **3.5** were distinctly different as the nitrogen atoms bonded to the phosphorus centers are of different hybridization. The average P-N bond distance to the nitrogen atom bound to the six-membered ring was 1.708(2) Å while that to the *sp*² hybridized nitrogen in the imidazole ring was 1.783(2) Å. The latter exocyclic P-N bond distance was in good agreement with that similar bonds present in reported cyclodiphosph(III)azane, [(μ -N(Dipp)CH(N))P(μ -N^{*t*}Bu)₂P]⁺[⁻OTf] (mean P-N(*sp*² hybridized): 1.792(2) Å).¹⁶⁸ The endocyclic P-N-P bond angles were in the range of 95.5(1) – 96.7(1)° and 97.9(1) – 98.1(1)° for **3.4** and **3.5**, respectively, which were similar to that found in the analog, [(*o*-NH(*t*Bu)C₆H₄)P(μ -N^{*t*}Bu)]₂ (97.2(2) – 98.4(2)°).¹⁸ The mean endocyclic N-P-N bond angles in both compounds were in good agreement with the reported cyclodiphosph(III)azane, [(PhHN)P(μ -N^{*t*}Bu)]₂ (82.1(6) and 81.4(1)° for **3.4** and **3.5**, respectively *cf.* 81.0(1)°).¹⁶⁴

3.3 – Orthogonal one-step mechanochemical syntheses of cyclodiphosph(V)azanes

Scheme 3.12. General reaction scheme for formation of cyclodiphosph(V)azanes.⁹¹

Moving forward, we proceeded to synthesize oxidized derivatives of the cyclodiphosph(III)azanes generated in the previous section, and further investigated on their air and hydrolytic stabilities as an extension of our previous reported work on enhanced stability of chalcogenic oxidized cyclodiphosphazanes.⁹¹ To generate bis(amino)- and bis(alkoxy)cyclodiphosph(V)azanes from compound **1.1** under

standard solution-based method, nucleophilic substitution is first carried out to obtain functionalized cyclodiphosphazane, followed by oxidation with appropriate agents such as hydrogen peroxide or elemental chalcogens (*Scheme 3.12*).⁹¹ Hence, we proposed to streamline this two-step synthetic procedure into orthogonal, one-step reaction with the use of ball milling.

3.3.1 - Results and discussion for orthogonal one-step syntheses of cyclodiphosph(V)azanes

Orthogonality in chemical reactions can be used as a strategy to truncate reaction steps and enable efficient formation of targeted products in a “one-pot” manner.¹⁶⁹ Orthogonality is often used interchangeably with chemoselectivity, and can be commonly described as two or more mutually exclusive reactions that proceed by different mechanisms.¹⁶⁹ The formation of selective products through orthogonal reactions is, to date, rare and limited.^{149,170,171} In this study, we have selectively synthesized a variety of cyclodiphosph(V)azanes *via* orthogonal one-step mechanochemical reactions.

Scheme 3.13. One-pot one-step mechanochemical syntheses of cyclodiphosph(V)azanes.

The reactions were conducted by loading a mixture of compound **1.1**, elemental chalcogen and appropriate organic acids along with triethylamine in the molar ratio of 1:3:2:2 into the milling jars, in an inert atmosphere glovebox, together with a 10 mm

stainless steel milling ball (*Scheme 3.13*). Once sealed, the mills were retrieved from the glovebox and milled at 30 Hz over a period of 3.5 to 10.0 hours. The crude reaction mixtures were isolated in the glovebox before taken out for filtration and purification. These subsequent workup procedures were performed using the Schlenk line under inert argon atmosphere. All the compounds were purified by recrystallization and the isolated crystals were dried under vacuum to give yields of 28 - 65%. The performed orthogonal mechanochemical reactions produced the desired cyclodiphosph(V)azanes in quantitative conversions, as indicated by the *ex situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra recorded of their crude reaction mixtures in THF. It is worth highlighting that, unlike the solution-based synthesis of bis(alkoxy)cyclodiphosph(V)azane, $[(p\text{-OC}_6\text{H}_4\text{CN})(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$,⁹¹ these mechanochemical reactions have enabled exclusive formation of only one product. The formation of sole product in each reaction was supported by the presence of single singlet resonance recorded on the $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra at δ 39.6, 25.6, 38.6, 22.9, 39.9, 30.4, 45.8 and 36.2 ppm for compounds **3.6** - **3.13**, respectively (*Fig. 3.4*).

Figure 3.4. *Ex situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra of compounds **3.6** – **3.13** in THF, illustrating exclusive formation of only one product.

An analogous solution-based synthesis of compound **3.11** was attempted and resulted in formation of mixture of products, as evidenced by the *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy recorded (minor signal at δ 42.6 and 31.9 ppm, and major signal at δ 21.4 ppm) (Fig. 3.5).

Figure 3.5. *In situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR of one-pot one-step solution-based reaction to synthesize compound **3.11**.

The ^1H NMR spectra of compounds **3.6** – **3.13** displayed resonance signals that were consistent with the presence of *tert*-butyl groups on the P_2N_2 rings and their respective functional moieties (1-adamantanol, 1-adamantylamine, *p*-aminobenzonitrile or mesitylamine). The FTIR absorption analyses further supported the proposed structures of compounds **3.8** – **3.13** with detection of characteristic N-H stretching bands at $\nu = 3379, 3366, 3235, 3287, 3175$ and 3125 , and 3294 cm^{-1} , respectively. In addition, the presence of nitrile groups in compounds **3.10** and **3.11** were confirmed by the observation of characteristic absorption bands ($\nu = 2220$ and 2224 cm^{-1}). All the spectroscopic data collected supported the successful formations of cyclodiphosph(V)azane **3.6** – **3.13** via mechanochemical milling.

3.3.2 - X-ray crystallography data for compounds 3.6 – 3.13

Single crystal X-ray diffraction (SC-XRD) studies were conducted to further elucidate the molecular structures of the synthesized compounds (**3.6** – **3.13**). The SC-XRD data were in good agreement with the *ex situ* ^{31}P - $\{^1\text{H}\}$ NMR studies, confirming the exclusive formation of only one product in each of the reactions. All the compounds obtained were found to adopt a *cis* conformation. To our surprise, no *trans* products were observed for compounds **3.6** – **3.9** despite the presence of bulky adamantyl substituents. This is unusual as one would normally expect the presence of such bulky substituents to favour formation of *trans* products so as to minimize the potential steric hindrance present when the compound adapt in the *cis* conformation.¹⁹

Figure 3.6. ORTEP drawing of the molecular structure of **3.6** (left) and **3.7** (right). Thermal ellipsoids with 50 % probability at 153 K. Hydrogen atoms and toluene solvate molecules for **3.6**, and hydrogen atoms for **3.7** are omitted for clarity. Compound **3.6**: Selected bond lengths (Å): P1-S1 1.9293(7), P2-S2 1.9299(6), P1-N1 1.6863(15), P1-N2 1.6886(15), P2-N1 1.6886(15), P2-N2 1.6893(15), P1-O1 1.5804(13), P2-O2 1.5746(13); Selected bond angles (°): N1-P1-N2 84.03(7), N1-P2-N2 83.94(7), P1-N1-P2 95.51(8), P1-N2-P2 95.40(8), O1-P1-N1 107.61(7), O1-P1-N2 106.80(7), O2-P2-N1 107.44(7), O2-P2-N2 107.40(7), N1-P1-S1 119.09(6), N2-P1-S1 119.21(6), N2-P2-S2 119.17 (6), N1-P2-S2 119.49(6), O1-P1-S1 115.58(5), O2-P2-S2 105.05(5); Compound **3.7**: Selected bond lengths (Å): P1-Se1 2.079(3), P2-Se2 2.085(3), P1-N1 1.693(7), P2-N1 1.691(7), P1-O1 1.579(9), P2-O2 1.565(8); Selected bond angles (°): N1-P1-N1 84.1(4), N1-P2-N1 84.2(5), P1-N1-P2 95.7(3), O1-P1-Se1 115.6(3), O2-P2-Se2 106.6(3), Se1-P1-N1 120.4(2), Se2-P2-N1 119.9(2).

The diffraction quality single crystals of **3.6**, **3.7** and **3.13** were obtained from recrystallization in toluene, while that of **3.8** and **3.9** were grown from a mixture of THF/toluene solution. Compound **3.10** was recrystallized as THF solvate from slow evaporation of THF solution containing **3.10**. While, compound **3.11** was recrystallized as a methanol solvate. Diffraction quality single crystals of compound **3.12** was obtained using chloroform as the recrystallization solvent.

The P-N bond distances (1.677(3) – 1.713(2) Å) within the P₂N₂ rings of all the synthesized compounds (**3.6** – **3.13**) were found to fall within the range of typical endocyclic P-N bond distances for cyclodiphosph(V)azane derivatives, [(ⁱBuHN)(E)P(μ -N^{*i*}Bu)]₂ (1.675(3) – 1.695(3) Å and 1.679(2) – 1.688(3) Å for E = S and Se respectively) and [(*p*-OC₆H₄CN)(E)P(μ -N^{*i*}Bu)]₂ (1.669(5) – 1.686(5) Å and 1.676(2) – 1.685(2) Å for E = S and Se respectively).^{91,93,172} The mean exocyclic P-O bond distances in **3.6** and **3.7** (1.578(1) and 1.572(9) Å, respectively) were comparable to that found in bis(alkoxy)cyclodiphosph(V)azanes, [(*o*-OCH₂C₆H₄N)(S)P(μ -N^{*i*}Bu)]₂ and [(Se)P(μ -N^{*i*}Bu)(OCH₂CH₂NMe₃)(I)]₂ (1.587(3) and 1.601(2) Å, respectively).^{173,174} On the other hand, the average exocyclic P-N bond distances in compounds **3.8** – **3.13** (1.633(4), 1.636(2), 1.645(2), 1.656(3), 1.647(1) and 1.653(2) Å, respectively) were in good agreement with the expected range of such cyclodiphosphazane compounds, [(NC₄H₈O)(S)P(μ -N^{*i*}Bu)]₂ and [(NC₄H₈(NMe))(Se)P(μ -N^{*i*}Bu)]₂ (1.648(1) and 1.644(2) Å, respectively).¹⁷⁵

Figure 3.7. ORTEP drawing of the molecular structure of **3.8** (left) and **3.9** (right). Thermal ellipsoids with 50 % probability at 100 and 103 K respectively. Hydrogen atoms and THF solvate molecule for **3.8**, and hydrogen atoms for **3.9** are omitted for clarity. Compound **3.8**: Selected bond lengths (Å): P1-S1 1.9286(18), P2-S2 1.9321(17), P1-N1 1.704(4), P2-N1 1.679(4), P1-N2 1.694(4), P2-N2 1.696(4), P1-N3 1.638(4), P2-N4 1.628(4); Selected bond angles (°): N1-P1-N2 82.9(2), N1-P2-N2 83.6(2), P1-N1-P2 96.7(2), P1-N2-P2 96.4(2), N1-P1-S1 117.66(16), N2-P2-S2 119.03(16), N1-P1-N3 110.2(2), N2-P2-N4 108.9(2); Compound **3.9**: Selected bond lengths (Å): P1-Se1 2.0841(6), P2-Se2 2.0817(6), P1-N1 1.7004(17), P1-N2 1.6926(18), P2-N1 1.7003(18), P2-N2 1.6966(17), P1-N3 1.6384(18), P2-N4 1.6334(19); Selected bond angles (°): N1-P1-N2 82.87(8), N1-P2-N2 82.75(8), P1-N1-P2 96.44(9), P1-N2-P2 96.88(9), N2-P1-N3 108.41(9), N2-P2-N4 108.22(9), N1-P1-Se1 118.84(7), N3-P1-Se1 113.96(7), N2-P2-Se2 120.65(7), N4-P2-Se2 113.09(7).

All four pairs of compounds, **3.6/3.7**, **3.8/3.9**, **3.10/3.11** and **3.12/3.13**, exhibited noticeable differences in their solid-state molecular structures. Despite being structural

analogs, in the pair of **3.6/3.7**, **3.6** adopted an *exo, exo* orientation while that of **3.7** was observed to exist in *exo, endo* manner (Fig. 3.6). In the set of **3.8/3.9** (Fig. 3.7), **3.8** recrystallized as a THF solvate with intermolecular hydrogen-bonding formed between the exocyclic N-H groups and the THF molecule. Despite being structurally similar, this interaction was not observed in compound **3.9**.

Figure 3.8. ORTEP drawing of the molecular structure of **3.10** (left) and **3.11** (right). Thermal ellipsoids with 50 % probability at 153 and 100 K respectively. Compound **3.10**: Hydrogen atoms, ammonium chloride and THF solvate molecules are omitted for clarity. Selected bond lengths (Å): P1-S1 1.9257(7), P2-S2 1.9193(7), P1-N1 1.6838(16), P1-N2 1.6843(17), P2-N1 1.6936(17), P2-N2 1.6855(17), P1-N3 1.6436(17), P2-N4 1.6460(17); Selected bond angles (°): N1-P1-N2 83.57(8), N1-P2-N2 83.24(8), P1-N1-P2 95.98(9), P1-N2-P2 96.26(9), N3-P1-N1 106.29(8), N3-P1-N2 108.53(9), N4-P2-N1 107.29(9), N4-P2-N2 107.19(9), N1-P1-S1 120.01(7), N2-P1-S1 120.05(6), N2-P2-S2 120.00(6), N1-P2-S2 120.06(6), N3-P1-S1 114.18(7), N4-P2-S2 114.63(6); Compound **3.11**: Hydrogen atoms and MeOH solvate molecules are omitted for clarity. Selected bond lengths (Å): P1-Se1 2.0741(11), P2-Se2 2.0788(10), P1-N1 1.677(3), P1-N2 1.688(3), P2-N1 1.690(3), P2-N2 1.684(3), P1-N3 1.660(3), P2-N5 1.652(3); Selected bond angles (°): N1-P1-N2 83.69(16), N1-P2-N2 83.45(17), P1-N1-P2 96.32(16), P1-N2-P2 96.15(17), N1-P1-N3 105.19(17), N2-P2-N5 104.41(17), N1-P1-Se1 121.55(12), N2-P2-Se2 122.41(12).

In the case of **3.10/3.11** pair, the aromatic rings in compounds **3.10** and **3.11** adopted slightly different orientations (Fig. 3.8), *i.e.* the phenyl rings in **3.10** were almost coplanar to each other whereas those in **3.11** were nearly perpendicular to each other. Moreover, it is worth pointing out that compound **3.10** recrystallized with one molecule of triethylammonium chloride and one solvate molecule of THF. The chloride anion was found to form bifurcated hydrogen bonds with the two exocyclic N-H protons and it also had charge-assisted hydrogen bonding with the proton of the triethylammonium cation (Fig. 3.9). This type of anion-hydrogen bonding was also seen in structural analog, $[(\text{ArHN})(\text{O})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (where Ar = Ph, *m*-(CF₃)₂Ph), reported by Goldfuss *et al.*¹⁷⁶

Figure 3.9. Interaction of chloride ion with the exocyclic NH protons and the proton of triethylammonium cation in the crystal structure of compound **3.10** (red dotted lines as the interactions). Hydrogen atoms, tert-butyl groups and THF solvate molecules are omitted for clarity. Only proton H1, H3 and H4 are shown for illustration of interaction. Triethylammonium cation are shown in wireframe for clarity.

While, for compound **3.11**, its molecules self-assembled to form a 1D supramolecular corrugated catemer held by intermolecular hydrogen-bonds between the methanol solvate molecules, exocyclic N-H protons and the nitrile group on the aromatic rings of the adjacent molecules (Fig. 3.10). To date, the only known cyclodiphosphazane example with such similar supramolecular 1D polymeric motif was reported by Balakrshina *et al.*. The *trans* cyclodiphosph(V)azane molecules, *trans*-[('BuHN)(Se)P(μ -NCy)]₂, were linked by water molecules *via* hydrogen-bond interaction, resulting in formation of linear hydrogen-bonded chains.⁸⁸

Figure 3.10. Fragment of the crystal structure of compound **3.11**, illustrating the formation of wave-like chains via formation of intermolecular hydrogen-bonds with methanol solvate molecules. The cyclodiphosph(V)azane molecules are shown in red and green while the methanol solvate molecules are shown in blue.

3.12

3.13

Figure 3.11. ORTEP drawing of the molecular structure of **3.12** (left) and **3.13** (right). Thermal ellipsoids with 50 % probability at 100 K. Compound **3.12**: Hydrogen atoms and triethylammonium chloride are omitted for clarity. Selected bond lengths (Å): P1-N1 1.6832(12), P1-N2 1.7080(11), P2-N1 1.6813(11), P2-N2 1.7054(12), P1-N3 1.6438(12), P2-N4 1.6503(12), P1-S1 1.9309(5), P2-S2 1.9287(5); Selected bond angles (°): N1-P1-N2 84.19(6), N1-P2-N2 84.33(6), N3-P1-N1 103.15(6), N3-P1-N2 114.29(6), P1-N1-P2 96.50(6), P1-N2-P2 94.67(6), S1-P1-N1 123.02(4), S2-P2-N2 117.10(4); Compound **3.13**: Hydrogen atoms and toluene solvate molecule are omitted for clarity. Selected bond lengths (Å): P1-N1 1.6960(19), P1-N2 1.7132(19), P2-N1 1.6849(19), P2-N2 1.6967(19), P1-N3 1.657(2), P2-N4 1.6496(19), P1-Se1 2.0702(6), P2-Se2 2.0941(6); Selected bond angles (°): N1-P1-N2 83.82(9), N1-P2-N2 84.66(9), N3-P1-N1 103.91(10), N3-P1-N2 113.93(10), P1-N1-P2 96.03(10), P1-N2-P2 94.95(10), Se1-P1-N1 121.87(7), Se2-P2-N2 116.92(7).

For the final pair of **3.12/3.13** (Fig. 3.11), compound **3.12** was recrystallized with inclusion of triethylammonium chloride, similar as that of compound **3.10**. However, the interactions of the chloride anion in the solid-state structure were found to be different. The chloride anion was found to have hydrogen-bonding interactions with the two exocyclic N-H protons of **3.12**, the proton of triethylammonium cation and an additional interaction with the C-H proton of another molecule of triethylammonium cation (Fig. 3.12).

Figure 3.12. Illustration of two molecules of compound **3.12** interacting with two molecules of triethylammonium chloride (interaction shown as red dotted lines). For clarity, the ethyl groups of the triethylammonium chloride and the mesitylene group were represented in wireframes while the tert-butyl groups and hydrogen atoms except H3-H5, H28D and H31A were omitted.

Figure 3.13. Illustration of hydrogen-bonding between molecules of compound **3.13**. The tert-butyl groups and hydrogen atoms except H3 and H4 were omitted for clarity.

On the other hand, compound **3.13** was recrystallized as a toluene solvate. The two selenium atoms on the same cyclodiphosphazane molecules interacted differently with their neighbouring molecules. According to the solid-state structure of **3.13**, one of the selenium atoms was observed to interact with the two exocyclic N-H protons of another P_2N_2 molecule to form bifurcated hydrogen-bonds. While the other selenium atom was found to have Se- π interaction with the aromatic ring of yet another adjacent molecule of **3.13** (Fig. 3.13).

3.4 - Air- and moisture-stability studies of compounds 3.6 – 3.11

Typically, phosphorus(V) species are more stable than their phosphorus(III) analogs. However, it has been illustrated by various groups that oxidation to phosphorus(V) does not warrant the compounds to be air- and moisture-stable. There are several examples showing that cyclodiphosph(V)azanes exhibited varied air- and moisture-stability. Some of these examples are illustrated as below.

Scheme 3.14. Reaction scheme for oxidation of bis(tert-butylamido)cyclodiphosph(III)azane, $[(^t\text{BuHN})P(\mu\text{-}N^t\text{Bu})]_2$, with chalcogens.¹⁷⁷

For example, Chivers *et al.* accounted the oxidation of bis(*tert*-butyl)cyclodiphosph(III)azane, $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$, with elemental sulfur and selenium to obtain bis(*tert*-butyl)cyclodiphosph(V)azanes, $[(^t\text{BuHN})(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (Scheme 3.14).^{172,177} The sulfide was found to be air- and moisture-stable, whereas the selenide derivative retained the sensitivity towards air and moisture from the parent compound, $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})]_2$.

Scheme 3.15. Reaction route to obtain cyclodiphosph(V)azane-based macrocyclic arrangements.⁷¹

Also, the same group reported the oxidation reactions to obtain trimeric cyclodiphosph(V)azane-based macrocycles (Scheme 3.15).⁷¹ In that same account, they further described the *S-S* bridged macrocycle to be air sensitive, while the *Se-Se* bridged analog was air stable. However, it is important to note that the sensitivity of these macrocycles may stem from the nature of the *E-E* bridges rather than the $\text{P}^{\text{V}}_2\text{N}_2$ rings.

Scheme 3.16. Oxidation reactions of cyclodiphosphazane, $[(p\text{-OC}_6\text{H}_4\text{CN})(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$, to obtain air- and hydrolytic-stable cyclodiphosph(V)azanes.⁹¹

Our group recently reported on the oxidation reactions to produce a series of chalcogen-oxidized bis(alkoxy)cyclodiphosph(V)azanes, $[(p\text{-OC}_6\text{H}_4\text{CN})(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ where $\text{E} =$

O, S or Se (*Scheme 3.16*). We conducted detailed air- and hydrolytic-stabilities studies on the synthesized compounds with the use of $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy. The three bis(alkoxy)cyclodiphosph(V)azanes were found to be extremely air stable over the course of 18 months – where the compounds were left on the shelves and NMR samples were prepared at regular intervals and the spectra were recorded accordingly. They were also hydrolytically stable over a wide range of temperature.⁹¹

*Scheme 3.17. Oxidation of cyclodiphosphazane hexamer, $[(\text{S})\text{P}^{\text{V}}(\mu\text{-N}^t\text{Bu})(\text{S})\text{P}^{\text{V}}(\mu\text{-S})\text{P}^{\text{III}}(\mu\text{-N}^t\text{Bu})\text{P}^{\text{III}}(\mu\text{-S})]_3$, to fully oxidized derivative, $[(\text{S})\text{P}^{\text{V}}(\mu\text{-N}^t\text{Bu})(\text{S})\text{P}^{\text{V}}(\mu\text{-S})]_6$.*⁷²

The same was further corroborated in macrocyclic arrangement - where the fully oxidized, S-bridged hexameric macrocycle was prepared from oxidation of mixed-valent parent compound, $[(\text{S})\text{P}^{\text{V}}(\mu\text{-N}^t\text{Bu})(\text{S})\text{P}^{\text{V}}(\mu\text{-S})\text{P}^{\text{III}}(\mu\text{-N}^t\text{Bu})\text{P}^{\text{III}}(\mu\text{-S})]_3$ (*Scheme 3.17*).⁷²

3.4.1 - Air stability studies of compounds 3.6 – 3.11

As an extension of our previous work, we evaluated the air and moisture stabilities of the newly synthesized compounds (**3.6** – **3.11**) using $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy.

Figure 3.4 $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum of compounds **3.6** – **3.11** after exposure to air for 1 day (bottom), 6 (middle), and 12 months (top), respectively (in THF).

NMR samples of compounds **3.6** – **3.11** were prepared by dissolving approximately 5 mg of the compound in 1 mL of THF at regular test intervals (*i.e.* monthly) throughout the course of study. The $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra of compounds **3.6** – **3.11** were monitored over a period of 12 months (Fig. 3.14). The $^{31}\text{P}\{-^1\text{H}\}$ NMR data recorded were analyzed and suggested that these newly synthesized bis(alkoxy)cyclodiphosph(V)azanes are “bench-top stable” and resistant to decomposition in air.

3.4.2 - Hydrolytic stability studies of compounds 3.6 – 3.11

Prior to the hydrolytic stability study, we first tested the solubility of compounds **3.6** – **3.11**. This was conducted to ensure that any change observed on the $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra during the hydrolytic stability studies is solely indicative of the compounds' stability, especially since it has been observed that some of these compounds

precipitated out of the solution upon standing at room temperature for 1-2 days (*Table 3.1*).

Acetone:water			Cpds	THF:water			
1:0	2:1	1:5		1:0	5:1	1:2	1:5
✓	✓	✗	3.6	✓	✓	✓	✗
✓	✗	✗	3.7	✓	✓	✗	✗
✓	✗	✗	3.8	✓	✓	✓	✗
✓	✗	✗	3.9	✓	✓	✓	✗
✓	✗	✗	3.10	✓	✓	✗	✗
✓	✓	✗	3.11	✓	✓	✗	✗

Table 3.1. Solubility of compounds 3.6 – 3.11 in different ratio of acetone:water and THF:water. Blue tick represents the sample can be dissolved while the red cross represents either insolubility of sample or the cyclodiphosph(V)azane was found to crystallize out upon leaving to stand for 1-2 days.

Different ratios of THF:water and acetone:water mixtures were tested on compounds **3.6 – 3.11**. The NMR samples of these compounds in the different ratio of THF:water and acetone:water were prepared and monitored over the course of 2 days. The data was consolidated and tabulated as shown in *Table 3.1*. It was observed that the ratio of acetone:water = 2:1 and THF:water = 1:2 were not suitable as some of the compounds precipitate out after standing at room temperature for 1 - 2 days. Therefore, after the series of solubility studies, we finalized the solvent system used for hydrolytic studies to be THF:water = 5:1.

Figure 3.15. $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra of compounds 3.6 – 3.11 in THF:water = 5:1 on Day 1 and after 14 days and 28 days.

Upon finalizing the solvent system as 5:1 THF:water ratio, the NMR samples of compounds **3.6** – **3.11** were prepared by taking approximately 5 mg of each compound and dissolved in 1 mL of THF:water = 5:1. The $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra were recorded over a period of 28 days. Based on the consolidated data, all synthesized compounds showed no sign of hydrolysis products over the tested period, except compound **3.9** which underwent slight hydrolysis (*Fig. 3.15*). Despite of that, compound **3.9** was observed to be still stable over 2 weeks with no obvious sign of hydrolysis – considerably enhancement from the parent compound. Hence, compounds **3.6** – **3.11** are tested to be air and hydrolytic-stable and they are new additions to the family of air- and water-stable cyclodiphosphazanes.

3.5 - Conclusion of the chapter

In conclusion, this chapter has demonstrated the use of mechanochemistry as a greener and synthetically efficient alternative for the syntheses of cyclodiphosphazane-based compounds. The switch from standard solution-based method to mechanochemical ball milling has resulted in shorter reaction times and higher yields. Cyclodiphosph(V)azanes **3.6** – **3.13** can be prepared from **1.1** directly *via* orthogonal one-pot one-step mechanochemical reaction, conveniently eliminating the need to isolate the phosphorus(III) species before oxidation and streamlined the synthetic procedure to a single step reaction. These phosphorus(V) derivatives (**3.6** – **3.11**) were tested and exhibited enhanced stability towards air and moisture – new members to the family of air- and water-stable cyclodiphosphazanes.

Chapter 4 - Synthesis of Macrocycles with P-OC(O) moiety

4.1 - Introduction

In the introductory chapter, we mentioned that dichlorocyclodiphosph(III)azanes, $[\text{ClP}(\mu\text{-NR})]_2$, are widely used in reactions with many different types of nucleophiles to generate functionalized cyclodiphosphazanes. In general, the nucleophilic substitution reactions are carried out with the use of amines, alcohols, thiols and organolithium reagents *etc.* Some examples of these nucleophile choices are illustrated in *Chapter 3*. To date, the reported acyclic disubstituted cyclodiphosph(III)azanes generally bear the newly formed P-C, P-N, P-O or P-S bonds from the nucleophilic substitution reactions carried out. There is no successful account on the formation of disubstituted cyclodiphosph(III)azanes, $[(\text{R}'(\text{O})\text{CO})\text{P}(\mu\text{-NR})]_2$, from the reaction of dichlorocyclodiphosph(III)azanes with carboxylic acid reported. Therefore, we are particularly interested in forming P-OC(O) bond in cyclodiphosphazane chemistry.

Scheme 4.1 (a) Arbuzov rearrangement of disubstituted cyclodiphosphazane, $[(\text{F}_3\text{C}(\text{O})\text{CO})\text{P}(\mu\text{-N}^t\text{Bu})]_2$, to give more stable $\text{P}=\text{O}$ derivative.¹⁷⁸ (b) Cyclodiphosphazane bearing P-OC(O) moiety prepared from diradicaloid $[\cdot\text{P}(\mu\text{-N}^t\text{Ter})]_2$.¹⁷⁹

There were a few records on formations of such bond being observed in cyclodiphosphazane chemistry. One of the earliest work was reported by Shreeve and co-workers. They reacted compound **1.1** with silver trifluoroacetate and identified the product to be a mixture of *cis/trans* acyclic disubstituted cyclodiphosph(III)azanes, $[(\text{F}_3\text{C}(\text{O})\text{CO})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ (^{31}P - $\{^1\text{H}\}$ NMR: δ 179.1 and 161.1 ppm, *trans* and *cis* respectively) (Scheme 4.1a). However, the disubstituted cyclodiphosph(III)azane was

found to be only marginally stable at 25 °C and for 12 hours under inert condition before it decomposed. It was confirmed by the gradual increase of new resonance signal at δ 3.88 ppm on $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum and the detection of absorption bands in the 1300-1100 cm^{-1} region on the FTIR spectra.¹⁷⁸ The acyclic disubstituted cyclodiphosph(III)azane was not isolated and these results therefore supported the occurrence of Arbuzov rearrangement to phosphorus(V) compound, $[(\text{F}_3\text{CC}(\text{O}))(\text{O})\text{P}(\mu\text{-N}^t\text{Bu})]_2$.

By contrast, Schulz *et al.* demonstrated successful isolation of $[(\text{F}_3\text{C}(\text{O})\text{CO})\text{P}(\mu\text{-N}^t\text{Ter})]_2$ prepared from reacting diradicaloid, $[\cdot\text{P}(\mu\text{-N}^t\text{Ter})]_2$, with silver trifluoroacetate (*Scheme 4.1b*).¹⁷⁹ This example was thus far the only cyclodiphosph(III)azane bearing P-OC(O) moiety reported. However, it is important to emphasize that the product was obtained from diradicaloid species rather than from nucleophilic substitution of dichlorocyclodiphosphazanes. Hence, the lack of such functionalized cyclodiphosph(III)azanes, $[(\text{R}'(\text{O})\text{CO})\text{P}(\mu\text{-NR})]_2$, prompted us to explore the reactions of dichlorocyclodiphosph(III)azanes with different carboxylic acids.

4.2 – Prior work

Scheme 4.2. Reaction schemes of compound **1.1** with various carboxylic acids.¹⁶⁶

Since the library of cyclodiphosph(III)azanes bearing P-OC(O) functionality is limited and scarce, we aimed to generate new members by performing reaction of compound **1.1** with a variety of carboxylic acids. Our group recently reported on one such reaction, producing acyclic disubstituted cyclodiphosph(III)azane, [(*p*-OC(O)C₆H₄CN)P(μ -N'Bu)]₂ (**4.1**) (*Scheme 4.2a*).¹⁶⁶ Compound **4.1** was successfully isolated and fully characterized. Encouraged by the positive result, we further performed analogous reactions with replacement of *p*-cyanobenzoic acid by *m*-chlorobenzoic acid and adamantyl 1-carboxylic acid (*Scheme 4.2*).

The *in situ* ³¹P-{¹H} NMR spectra of the reactions showed only one singlet resonance signal at δ 175.5 and 175.1 ppm, suggestive of formations of disubstituted cyclodiphosph(III)azanes, [(*m*-OC(O)C₆H₄Cl)P(μ -N'Bu)]₂ (**4.2**) and [(Ad(O)CO)P(μ -N'Bu)]₂ (**4.3**) respectively. To date, no pure sample of **4.2** was isolated despite the numerous attempts made. The difficulty in obtaining pure sample of compound **4.2** may be due to the possible rearrangement occurring as indicated by appearance of resonance signals in the phosphorus(V) region (at δ 1.2 (d, coupling constant of 14.7 Hz) ppm) on the ³¹P-{¹H} NMR spectrum recorded over time. On the other hand, compound **4.3** was successfully isolated as pure solid and characterizations were subsequently carried out. The ¹H NMR spectrum of **4.3** exhibited broad singlet resonance signals with intensity ratios of 2:1:2:3 at δ 2.07, 1.90, 1.60 and 1.37 ppm, respectively, supporting the presence of *tert*-butyl and adamantyl substituents. The characteristic C=O resonance signal recorded at δ 176.8 ppm on ¹³C NMR spectrum confirmed the retainment of carboxyl (C=O) group. The presence of carboxyl moiety was also further corroborated by Fourier-Transform Infra-red (FTIR) spectroscopy with characteristic absorption band at ν = 1711 cm⁻¹. Despite having the pure sample of compound **4.3**, diffraction quality single crystals were yet to be obtained.

4.3 - Formation of macrocycles bearing P-OC(O) moiety

With the successful formation of acyclic disubstituted cyclodiphosph(III)azanes bearing P-OC(O) functionality, we moved on to perform the reactions to generate cyclic derivatives.

Scheme 4.3. Formation of cyclic cyclodiphosphazane-based compounds prepared from compound **1.1**.

Cyclodiphosphazane-based hybrid macrocycles are those prepared from the reactions of dichlorocyclodiphosphazane and bifunctional organic linkers (**HLL'H**). To date, there is a large volume of hybrid P_2N_2 macrocycles reported. The syntheses are generally carried out *via* solution-based method, reacting equimolar amounts of compound **1.1** and bifunctional organic linker in the presence of triethylamine (Scheme 4.3). Depending on the nature of the organic linkers used, it is possible to afford a mixture of P_2N_2 products. The reaction can result in a mixture of varied size cyclic products or, for cases where asymmetric organic linker was used, *cis/trans* isomers mixture.

Scheme 4.4. Reactions of compound **1.1** with 1,3-dihydroxybenzene and 1,4-dihydroxybenzene.^{56,180}

For instance, it was observed that the positions of functional groups on the organic linkers have some degree of influence on the reaction products formed. A pair of such cases are the reactions of compound **1.1** with 1,3-dihydroxybenzene and 1,4-dihydroxybenzene, reported by Balakrishna *et al.* and Wright *et al.*, respectively (*Scheme 4.4*).^{56,180} Balakrishna and co-workers reported the formation of both dimeric and tetrameric macrocycles in the reaction of **1.1** and 1,3-dihydroxybenzene. While, Wright and co-workers accounted their isolation of only trimeric macrocycles when the analogous reaction was performed with 1,4-dihydroxybenzene. The difference in ring size of the reaction products can be attributed to the position of functional groups on the organic linkers, which affects the propagation angle (*i.e.* P-O-C angle).

Scheme 4.5. Reactions of compound 1.1 with 1,2-diaminobenzene and 1,4-diaminobenzene.^{78,181}

The importance of the positions of the functional groups on the organic linker is, once again, highlighted in the reactions of compound **1.1** with 1,2-diaminobenzene and 1,4-diaminobenzene which gave rise to different sized macrocycles, respectively (*Scheme 4.5*).^{78,181}.

All these examples therefore highlight the effect of the positions of functional groups on the organic linkers on the size of the macrocycles generated in the reactions.

Henceforth, apart from synthesizing macrocyclic arrangements bearing P-OC(O) moiety, we also intended to investigate if such effect would be observed in the cases when isomeric dicarboxylic acids were used to react with compound **1.1**.

4.3.1 - Results and discussion for syntheses of macrocycles with P-OC(O) functionality

Figure 4.1. List of bifunctional organic linkers used for this study to form cyclic compounds.

Like the typical synthesis of hybrid cyclodiphosph(III)azane macrocycles, compound **1.1** was reacted with equimolar amount of bifunctional organic linker in presence of triethylamine. For this study, six different bifunctional organic linkers were utilized (*Fig. 4.1*). Aromatic carboxylic acids are generally more rigid than the aliphatic derivatives. Hence, to avoid linear propagation and direct the reaction towards formation of cyclic products, aromatic acids that are structurally rigid were chosen as linkers. Six organic nucleophiles were used - two of which bore hydroxyl and acid functionality, and the other four were dicarboxylic acids.

The asymmetric organic nucleophiles (*i.e.* *p*-hydroxybenzoic acid and 6-hydroxy-2-naphthoic acid) were chosen to study the effect of the size (phenyl vs. naphthyl) of the organic linkers on the topology of the cyclic products generated in the reactions. In

addition, isomeric dicarboxylic acid (*i.e.* phthalic, isophthalic and terephthalic acid) were selected to investigate the influence of the substitution pattern (*ortho*- vs. *meta*- vs. *para*-substituted benzene). In the later part of the project, 5-*tert*-butylisophthalic acid was also employed to further study the effect on the cavity shape of the resulting macrocycle after the introduction of bulky group on the organic linker.

The reactions of compound **1.1** with chosen aromatic organic linkers were conducted using the mechanochemical milling techniques, as described in the previous chapter (Chapter 3). The mechanochemical reactions were carried out using a 10 mL stainless steel milling jar and a 10 mm milling ball. The mixture of one equivalent of **1.1** and an equimolar amount of appropriate acid, along with two equivalents of triethylamine, were loaded into the jars in an argon-filled glovebox.¹⁶⁶ The mixture was milled at 30 Hz for a period of 2 to 8 hours and the reactions were monitored by *ex situ* ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy. The NMR samples were prepared by taking about 5 mg of crude reaction mixture and dissolved in 1 mL of THF. The *ex situ* ^{31}P - $\{^1\text{H}\}$ NMR spectra were recorded immediately upon completed preparation of the NMR samples.

Scheme 4.6. Reaction schemes for formation of compounds **4.4** and **4.5** from **1.1** with *p*-hydroxybenzoic acid and 6-hydroxy-2-naphthoic acid, respectively.¹⁶⁶

Both the reactions with *p*-hydroxybenzoic acid and 6-hydroxy-2-naphthoic acid resulted in formation of only *trans* macrocycles (**4.4** and **4.5**), as supported by the presence of two sets of doublets on the ^{31}P - $\{^1\text{H}\}$ NMR spectra recorded (δ 142.8 (d, $^2J_{\text{P-P}} = 22.7$ Hz), 139.9 (d, $^2J_{\text{P-P}} = 22.7$ Hz), and 145.9 (d, $^2J_{\text{P-P}} = 22.7$ Hz), 141.5 (d, $^2J_{\text{P-P}} = 21.1$ Hz) ppm respectively) (Scheme 4.6). The exclusive formations of compounds **4.4** and **4.5** were distinctly different from that of previously reported reactions (*i.e.* the mixtures of *cis* and *trans* dimeric macrocycles with the use of 2-aminophenol and 2-aminothiophenol).⁷⁹

Scheme 4.7. Reaction scheme for syntheses of compounds **4.6** and **4.7** from **1.1** and isophthalic and terephthalic acid, respectively.¹⁶⁶

The reactions of compound **1.1** with isophthalic acid and terephthalic acid were then performed. Both reactions resulted in quantitative conversion of compound **1.1** to corresponding cyclic products, indicated by the presence of only one resonance signal on their *ex situ* ^{31}P - $\{^1\text{H}\}$ NMR spectra (δ 171.2 and 189.9 ppm respectively) (Scheme 4.7). The products were identified to be both dimeric macrocycles *via* SC-XRD studies of the single crystals obtained. These results were distinctly different from previously reported examples where the modification on the aromatic ring substituents positions generally led to cyclodiphosphazane macrocycles of varied sizes. The exclusive

formation of these dimeric macrocycles was likely attributed to the more acute angle of propagation (*i.e.* P-O-C(O) bond angle), as compared to that of P-O-C, induced by the presence of the carboxyl group.

The absence of O-H and P=O stretching absorption bands ($\nu = 3200$ and 1300 cm^{-1} , respectively), and the presence of C=O absorption band at $\nu = 1680\text{ cm}^{-1}$, on the FTIR spectra, supported the presence of P-OC(O) functionality in all the four macrocycles. Our data suggested that the compounds synthesized, unlike $[(F_3C(O)CO)P(\mu\text{-}N^t\text{Bu})]_2$, are stable at $25\text{ }^\circ\text{C}$ and did not undergo Arbuzov rearrangement to the more stable P=O derivatives.

Scheme 4.8. Reaction of compound **1.1** and 5-*tert*-butylisophthalic acid to obtain macrocycle **4.8**.

An analogous reaction with 5-*tert*-butylisophthalic acid was further carried out to evaluate any effect of the additional bulky *tert*-butyl group on the aromatic rings on the outcome of the reaction (Scheme 4.8). The *ex situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy revealed a singlet resonance signal at $\delta\ 165.4\text{ ppm}$, suggesting exclusive formation of one product. Upon filtration and purification steps, the reaction resulted in cyclic arrangement **4.8** with crystalline yield of 56 %. The single crystals obtained for **4.8** were analyzed *via* SC-XRD and found to be dimeric macrocycle.

Scheme 4.9. Reaction of compound **1.1** and phthalic acid resulting in formation of phthalic anhydride (**4.9**).

It is important to mention for the case of phthalic acid, we did not isolate any macrocyclic product from the reaction (Scheme 4.9). Surprisingly, the *ex situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum showed no resonance signal in the region of δ 150 - 200 ppm - typical of the P-OC(O) moiety. Instead, a singlet resonance signal at approximately δ -14 ppm, indicative of a phosphorus(V) center, was observed. Attempts to isolate compound corresponding to this resonance signal were performed, but to no avail to date.

Figure 4.2. Crystal structure of compound **4.9** as determined by X-ray diffraction crystallography. Thermal ellipsoids with 50 % probability at 103 K. Hydrogen atoms are omitted for clarity.

Instead, the crystals grown from the reaction solution were identified as phthalic anhydride (**4.9**) by SC-XRD (Fig. 4.2). The isolation of phthalic anhydride suggested that the reaction had likely undergone some unintended rearrangement.

Scheme 4.10. Reactions involving phthalic acid and phosphorus-based reactants resulting in phthalic anhydride.^{182,183}

With further research into literature, we found records on similar reactions involving the use of phosphorus-containing reactants and phthalic acid resulting in the formation of phthalic anhydride (*Scheme 4.10*).^{182,183} For example, Kim *et al.* reported that various acid anhydrides can be accessed from reacting triphenylphosphine, corresponding carboxylic acid, trichloroacetonitrile and triethylamine in THF at room temperature .¹⁸²

4.3.2 - X-ray crystallography data for compounds **4.4** - **4.8**

The newly synthesized macrocycles **4.4** - **4.8** were successfully recrystallized and characterized by SC-XRD. All the cyclic compounds were identified as dimeric macrocycles ($n = 2$) and contained the desired P-OC(O) moiety (*Fig. 4.3 – 4.5*). All compounds except **4.8** crystallized in triclinic crystal system while **4.8** crystallized in monoclinic crystal system.

4.4

4.5

Figure 4.3. ORTEP drawing of the molecular structure of compounds **4.4** (top) and **4.5** (below). Top view of the molecular structures are shown on the left while the side view ones are figures on the right. The tert-butyl groups in top view illustration are drawn as wireframes. Thermal ellipsoids with 50 % probability at 296 K. Hydrogen atoms are omitted for clarity. Compound **4.4**: Selected bond lengths (Å): P1-N1 1.723(3), P1-N2 1.709(3), P2-N1 1.709(3), P2-N2 1.705(3), P1-O1 1.660(3), P2-O2 1.709(2); Selected bond angles (°): N1-P1-N2 81.57(14), N1-P2-N2 82.11(14), P1-N1-P2 97.00(15), P1-N2-P2 97.70(16), N1-P1-O1 107.14(14), N1-P2-O2 104.52(14), N2-P1-O1 105.67(14), N2-P2-O2 97.15(13), C9-O1-P1 127.9(2); Compound **4.5**: Selected bond lengths (Å): P1-N1 1.710(4), P1-N2 1.692(3), P2-N1 1.709(3), P2-N2 1.708(3), P3-N3 1.693(4), P3-N4 1.698(4), P4-N3 1.705(4), P4-N4 1.708(4), P1-O1 1.697(3), P2-O3 1.632(3), P3-O4 1.705(3), P4-O6 1.653(4); Selected bond angles (°): N1-P1-N2 82.12(16), N1-P2-N2 81.68(16), N3-P3-N4 82.08(19), N3-P4-N4 81.40(18), P1-N1-P2 97.07(17), P1-N2-P2 97.79(17), P3-N3-P4 97.77(18), P3-N4-P4 97.45(18), N1-P1-O1 104.27(16), N2-P1-O1 97.45(16), N3-P3-O4 97.28(17), N4-P3-O4 103.81(18), N2-P2-O3 106.48(16), N1-P2-O3 108.70(17), N4-P4-O6 107.22(19), N3-P4-O6 105.65(19).

First, we compared the solid-state structures of **4.4** and **4.5** prepared from compound **1.1** with asymmetric organic linkers (*Fig. 4.3*). The endocyclic P-N bond lengths and bond angles in both **4.4** and **4.5** were close to the reported range of these parameters in cyclodiphosph(III)azane analog, [(F₃C(O)CO)₂P(μ-NTer)]₂.¹⁷⁹ There were two types of P-O bonds (*i.e.* P-O(hydroxy) and P-O(carboxyl)) in both *trans* cyclic arrangements **4.4**

and **4.5**. The difference between the two P-O bonds was readily illustrated in both compounds, where the P-O(carboxyl) bonds were found to be longer than the P-O(hydroxy) bonds. The P-O(hydroxy) and P-O(carboxyl) bond distances were measured to be 1.660(3) and 1.709(2) Å for **4.4** and, 1.642(4) and 1.701(3) Å for **4.5**. Both **4.4** and **4.5** possessed narrow elliptic, cylinder-shaped cavities. The sizes of cavities were measured to be 8.097 and 11.191 Å, respectively, between the centroids of the two P₂N₂ rings, and 3.058 and 3.289 Å, respectively, between the calculated mean planes of the aromatic groups for **4.4** and **4.5**.¹⁶⁶

4.6

4.7

Figure 4.4. ORTEP drawing of the molecular structure of compounds **4.6** (top) and **4.7** (below). Top view of the molecular structures are shown on the left while the side view ones are figures on the right. The tert-butyl groups in top view illustration are drawn as wireframes. Thermal ellipsoids with 50 % probability at 103 K. Hydrogen atoms are omitted for clarity. Compound **4.6**: Selected bond lengths (Å): P1-N1 1.703(4), P1-N2 1.719(4), P2-N1 1.706(4), P2-N2 1.718(4), P3-N3 1.713(4), P3-N4 1.696(4), P4-N3 1.694(4), P4-N4 1.710(4), P1-O7 1.705(3), P2-O1 1.704(3), P3-O3 1.721(3), P4-O5 1.708(3); Selected bond angles (°): N1-P1-N2 82.04(17), N1-P2-N2 81.98(18), N3-P3-N4 81.78(17), N3-P4-N4 81.94(17), P1-N1-P2 97.13(19), P1-N2-P2 96.09(19), P3-N3-P4 97.40(19), P3-N4-P4 97.46(19), N1-P1-O7 98.61(17), N2-P1-O7 103.41(18), N1-P2-O1 98.25(17), N2-P2-O1 103.27(17), N3-P3-O3 99.13(17), N4-P3-O3 104.56(17), N3-P4-O5 98.22(17), N4-P4-O5 104.78(17); Compound **4.7**: Selected bond lengths (Å): P1-N1 1.6956(18), P1-N2 1.631(17), P2-N1 1.6964(17), P2-N2 1.6939(17), P1-O8 1.7343(15), P2-O5 1.7338(15); Selected bond angles (°): N1-P1-N2 81.99(8), N1-P2-N2 81.94(8), P1-N1-P2 97.88(9), P1-N2-P2 98.08(9), N1-P1-O8 101.80(8), N1-P2-O5 96.64(8), N2-P1-O8 96.10(8), N2-P2-O5 102.74(8).

Moving on, we compared the solid-state structures of **4.6** and **4.7** to examine how the functionality positions on the organic linker can influence the reaction product formed (Fig. 4.4). Despite both being dimeric cyclic compounds, the solid-state structures of

4.6 and **4.7** were distinctly different. Compared to the pair of **4.4** and **4.5**, the structural differences between this pair (**4.6/4.7**) were much more explicit. For example, the shape and size of the cavity in these two dimeric macrocycles. The molecular structure of compound **4.6** revealed a frustum-shaped cavity, resembling that of calixarenes. The size of its cavity was measured to be 8.939 Å between the centroids of the aromatic rings and 7.557 Å between the centroids of the two P₂N₂ rings. On the other hand, the molecular shape of **4.7** resembled closely to that observed in macrocycle **4.4** and **4.5**. However, the cavity within **4.7** was much ‘narrower’ as compared to the other two macrocycles, with its distance between the calculated mean planes of the aromatic groups to be 2.767 Å (*cf.* 3.058 and 3.289 Å for **4.4** and **4.5** respectively). In both **4.6** and **4.7**, the exocyclic oxygen atoms were oriented in *endo*, *endo* manner unlike the commonly observed *exo*, *endo* arrangements as seen in the previous pair of **4.4/4.5**.¹⁶⁶

Figure 4.5. ORTEP drawing of the molecular structure of compound **4.8**. The *tert*-butyl groups are drawn as wireframes. Thermal ellipsoids with 50 % probability at 100 K. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å): P1-N1 1.6955(17), P1-N2 1.7021(18), P2-N1 1.6995(17), P2-N2 1.7035(17), P3-N3 1.6904(17), P3-N4 1.6980(17), P4-N3 1.6927(17), P4-N4 1.6992(17), P1-O1 1.7247(14), P2-O3 1.7187(14), P3-O5 1.7275(14), P4-O7 1.7321(15); Selected bond angles (°): N1-P1-N2 82.64(8), N1-P2-N2 82.48(8), N3-P3-N4 81.98(8), N3-P4-N4 81.87(8), P1-N1-P2 97.48(9), P1-N2-P2 97.07(9), P3-N3-P4 98.34(9), P3-N4-P4 97.80(9), N1-P1-O1 96.44(8), N1-P2-O3 96.35(8), N3-P3-O5 97.92(8), N3-P4-O7 98.29(8).

As the molecular structure of compound **4.6** resembled that of calixarene, we introduced some steric bulk onto the organic linkers to attempt to increase the depth of the cavity in the molecular structure of the resulting compound (*i.e.* **4.8**), to make it further

resembles calixarene. Upon successful recrystallization of **4.8**, it was identified to be a dimeric macrocycle by SC-XRD. This therefore suggested that the additional *tert*-butyl group has no effect on the size of the cyclic product obtained. Moreover, it was observed that presence of additional *tert*-butyl substituents did not lead to any significant structural difference as compared to that of compound **4.6**, which does not contain any bulk group on the organic linker. Instead, the solid-state structure of compound **4.8** resembled closely to that of **4.6** (Fig. 4.5). The average P-O(carboxyl) bond distance in **4.8** (1.726 Å) was slightly longer than that calculated for **4.6** (1.710 Å). In the case of compound **4.8**, the resultant cavity had a more squarish shape with the distances measured between the centroids of the aromatic systems and the P₂N₂ rings to be 7.897 and 7.940 Å respectively.

With these structural data of compounds **4.4** – **4.8**, it seemed possible to further extrapolate the idea of developing cyclodiphosphazane-based macrocycles with varied cavity sizes. Therefore, as part of the proposed future work for this class of cyclic arrangements, our group is currently investigating on their potential applicability in host-guest chemistry.^{69,70,184}

4.4 - Oxidations of dimeric macrocycle **4.4 bearing P-OC(O) moiety**

As compounds **4.4** – **4.8** were the first five examples of cyclodiphosph(III)azane-based macrocycles bearing P-OC(O) moiety, it is of our interest to further study the behaviour of these compounds. Specifically, we are interested in accessing the stability of the P-OC(O) moiety towards further functionalization. It is worth highlighting that from the solid-state structures of **4.4** and **4.5**, it was noticed that the P-O(carboxyl) bonds present were evidently longer than the typical P-O(hydroxy) bonds.¹⁶⁶ We proceeded to carry

out oxidation reactions on compound **4.4** to attempt to selectively oxidize the phosphorus centers.

4.4.1 - Results and discussion on the oxidation reactions of **4.4** with elemental sulfur

Scheme 4.11 Reactions with elemental sulfur to generate compound **4.10** and further oxidations to obtain tetra-oxidized macrocycles.

The oxidation reaction of compound **4.4** was carried out in refluxing toluene with addition of two equivalents of elemental sulfur. The oxidation reaction successfully led to formation of mixed valent cyclodiphosphazane-based macrocycle, **4.10** (Scheme 4.11). The *in situ* ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy revealed two sets of doublets centered at δ 107.3 ($^2J_{\text{P-P}} = 17.8$ Hz) and 52.6 ($^2J_{\text{P-P}} = 19.4$ Hz) ppm as major peaks, indicative of the successful oxidation on two of the four phosphorus centers. The chemical shifts recorded were found to be similar to that of mixed valent acyclic disubstituted cyclodiphosphazane, $[(2\text{-OCH}_2\text{C}_5\text{H}_4\text{N})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{S})(2\text{-OCH}_2\text{C}_5\text{H}_4\text{N})]$, reported by Balakrishna *et al.* (^{31}P - $\{^1\text{H}\}$ chemical shifts: δ 91.6 (d, $^2J_{\text{P-P}} = 14.0$ Hz) and 57.1 (d) ppm).¹⁷³ With closer examination, another two sets of doublets were recorded as minor resonance signals on the *in situ* ^{31}P - $\{^1\text{H}\}$ NMR spectrum. The minor resonance signals

were in the typical region for P(hydroxy)=S moiety,^{16,185} centered at δ 53.2 ($^2J_{\text{P-P}} = 17.8$ Hz) and 48.6 ($^2J_{\text{P-P}} = 17.8$ Hz) ppm. These peaks were presumed to be corresponding to the tetra-sulfide derivative. The ^1H NMR spectroscopy of the purified solid showed resonance signals centered at δ 7.57 (d, $^3J_{\text{H-H}} = 8.8$ Hz), 7.33 (dd, $^4J_{\text{P-H}} = 1.6$ Hz, $^3J_{\text{H-H}} = 8.8$ Hz) and 1.54 (s), supportive of the retainment of the macrocyclic ring and the presence of *para*-substituted aromatic ring.

We conducted further oxidation reactions on *in situ* generated **4.10** to produce fully oxidized species (**4.10a-c**) (Scheme 4.11). Two equivalents of *meta*-chloroperbenzoic acid (*m*-CPBA) or *tert*-butyl hydroperoxide was added to a solution of *in situ* generated **4.10** and the reaction proceeded to result in formation of **4.10a** as the only isolated product. The $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum of **4.10a** revealed resonance signals in the region corresponding to P=S (δ 38.7 ppm, d, $^2J_{\text{P-P}} = 45.4$ Hz) and P=O (δ -9.6 ppm, d, $^2J_{\text{P-P}} = 43.7$ Hz) moieties. The ^1H NMR spectrum showed resonance signals at δ 7.71, 7.39 and 1.64 ppm with intensity of 2:2:9, suggested the macrocyclic ring remained intact. To generate the tetra-sulfide derivative **4.10b**, second batch of two equivalents of elemental sulfur was added to the solution containing *in situ* generated compound **4.10**. The *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy of the reaction revealed resonance signals similar to the minor resonance signals (δ 50.5 and 45.6 ppm) recorded on the *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum for the synthesis of **4.10**. It was later confirmed that **4.10b** could be accessed by direct oxidation of compound **4.10** with excess elemental sulfur in refluxing toluene. In the case of oxidation reaction of compound **4.10** with two equivalents of elemental selenium, the *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy showed two sets of doublets centered at δ 43.0 ($^2J_{\text{P-P}} = 16.7$ Hz), 26.0 ($^2J_{\text{P-P}} = 15.0$ Hz) ppm, suggesting possible formation of mixed chalcogenide macrocycle (**4.10c**). However, the diffraction quality single crystals of compound **4.10c** has yet to be obtained to date. In addition, the solid isolated was not

qualitatively pure to be conclusive of the successful formation, despite the observation of distinct peaks (*i.e.* two sets of doublets in the aromatic region (δ 7.65 – 7.34 ppm) and singlet signals at δ 1.74 ppm) on the ^1H NMR spectrum. The family of mixed chalcogenide cyclodiphosphazane compounds is highly limited with only a handful of examples reported to date. Some examples are $[(2\text{-OCH}_2\text{C}_5\text{H}_4\text{N})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{S})(2\text{-OCH}_2\text{C}_5\text{H}_4\text{N})]$ and $(R)\text{-}[(6,6\text{-}(^t\text{Bu})_2\text{C}_{20}\text{H}_{10}\text{O}_2)[(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{O})]$.^{173,186} Hence, the formation of these mixed chalcogenide cyclodiphosphazane-based macrocycles (**4.10a** and **4.10c**) is desired to expand this class of compounds.

4.4.2 - X-ray crystallography studies of compounds **4.10** and **4.10a-b**

Figure 4.6. Solid-state structure of compound **4.10**. The tert-butyl groups are drawn as wireframes. Thermal ellipsoids with 50 % probability at 203 K. Hydrogen atoms and tetrahydrofuran solvate molecules are omitted for clarity. Selected bond lengths (Å): P1-S1 1.9097(14), P1-O3 1.610(2), P2-O1 1.676(2), P1-N1 1.666(3), P1-N2 1.658(3), P2-N1 1.717(2), P2-N2 1.711(3); Selected bond angles (°): N1-P1-N2 84.58(12), N1-P2-N2 81.47(12), P1-N1-P2 96.22(12), P1-N2-P2 96.70(13), N1-P1-O3 109.83(12), N2-P1-O3 110.70(13), O1-P2-N1 103.70(12), S1-P1-O3 106.73(9), P1-O3-C13 126.07(18).

Mixed valent cyclodiphosphazane macrocycle **4.10** was successfully isolated and recrystallized from saturated THF solution. It crystallized in a monoclinic crystal system and was found to have an inversion center in the molecular structure of **4.10** (Fig. 4.6). Based on the solid-state structure of compound **4.10**, it was identified that the first oxidation took place at the P(hydroxy) centers rather than P(carboxyl) ones. It was proposed that it could be due to the presence of electron-withdrawing carboxyl moiety,

making the P(carboxyl) atoms less susceptible to oxidation. In addition, the SC-XRD further confirmed the retainment of the entire macrocyclic arrangement. The cavity within **4.10** was measured to be 8.824 and 2.608 Å between the centroids of the two P₂N₂ rings and calculated mean planes of the aromatic groups, respectively. The cavity size was slightly shorter and significantly narrower as compared to its parent macrocycle **4.4** (*cf.* 8.907 and 3.058 Å, respectively). Upon oxidation, both P(hydroxy)-O (1.610(2) Å) and P(carboxyl)-O (1.676(2) Å) bonds were shortened as compared to the non-oxidized species (**4.4**) (1.660(3) and 1.709(2) Å, respectively). The mean N-P(hydroxy)-O bond angle was calculated to be 110.3(1)° which was greater than that measured in **4.4** (106.4(1)°). While the P(hydroxy)-O-C bond angle was measured as 126.1(2)°, smaller than that in its parent compound **4.4**. This small reduction in bond angle was likely due to the occupancy of sulfur atom in **4.10**.

Figure 4.7. Solid-state structure of compounds **4.10a** (left) and **4.10b** (right). The tert-butyl groups are drawn as wireframes. Thermal ellipsoids with 50 % probability at 110 and 100 K, respectively. Hydrogen atoms and tetrahydrofuran solvate molecules are omitted for both compounds for clarity. Compound **4.10a**: Selected bond lengths (Å): P1-O1 1.436(7), P2-S1 1.909(2), P1-O3 1.619(2), P2-O5 1.596(3), P1-N1 1.669(3), P1-N2 1.662(3), P2-N1 1.682(3), P2-N2 1.674(3); Selected bond angles (°): N1-P1-N2 85.37(15), N1-P2-N2 84.59(15), P1-N1-P2 94.39(15), P1-N2-P2 94.95(15), N1-P1-O1 122.7(3), O1-P1-O3 112.6(3), S1-P2-N1 122.48(13), S1-P2-O5 108.22(11), P2-O5-C9 125.2(2); Compound **4.10b**: Selected bond lengths (Å): P1-S1 1.9041(8), P2-S2 1.9135(8), P1-O1 1.6270(15), P2-O3 1.6045(16), P1-N1 1.6816(18), P1-N2 1.6788(19), P2-N1 1.6752(18), P2-N2 1.6841(19); Selected bond angles (°): N1-P1-N2 84.76(9), N1-P2-N2 84.80(9), P1-N1-P2 94.95(9), P1-N2-P2 94.73(9), N1-P1-O1 100.59(9), N2-P2-O3 109.19(9), S1-P1-N1 122.49(7), S2-P2-N2 121.29(7), P2-O3-C14 124.71(14).

Diffraction quality single crystals of both **4.10a** and **4.10b** were obtained from recrystallization in THF. The molecular structures of the two compounds, as determined

by SC-XRD crystallography, are shown as *Fig. 4.7*. The SC-XRD data for **4.10a** further confirmed that the stoichiometric oxidation selectively occurred at the P(hydroxy) first and subsequently took place at P(carboxyl) – sulfur attached to the P(hydroxy) centers whereas oxygen attached to the P(carboxyl) ones.

The molecular structures of **4.10** and **4.10a-b** bear various similarities. The P=O bond distance in **4.10a** was measured to be 1.436(7) Å, comparable to that observed in dioxide cyclodiphosphazane-based compound, [(2,6-Me₂C₆H₃O)(O)P(μ -N^tBu)]₂ (mean P=O bond distance: 1.449(2) Å).¹⁸⁷ The P(hydroxy)-S bond distance observed in mixed chalcogenide compound **4.10a** was found to be 1.909(2) Å. Whereas, in the tetra-sulfide derivative **4.10b**, it was measured to be 1.904(1) and 1.914(1) Å for P(carboxyl)-S and P(hydroxy)-S bonds respectively. It was noticed that upon the second oxidation, the P(carboxyl)-O bond distances in both **4.10a** and **4.10b** had significantly shortened as compared to that in the mixed valent derivative **4.10** (1.619(2) and 1.627(2), respectively *cf.* 1.676(2) Å). The bond angles in both **4.10a** and **4.10b** were comparable to each other. For instance, the mean N-P(hydroxy)-O bond angles in **4.10a** and **4.10b** were calculated to be 109.6(2) and 109.4(1)°.

It was worth noting that the aromatic rings were observed to be almost parallel to each other in all three solid-state structures of compounds **4.10** and **4.10a-b**. The distances between the centroids of the aromatic rings were measured to be 5.163, 5.191 and 5.189 Å for **4.10** and **4.10a-b** respectively. The cavity sizes in **4.10a** and **4.10b** were found to be almost identical, with the distances between centroids of the P₂N₂ rings being 8.760 Å for both macrocycles. While, the distances between the calculated mean planes of the aromatic system were found to be 2.705 and 2.755 Å, respectively.

4.5 - First tetrameric macrocycle from asymmetric organic linker

In theory, the use of asymmetric organic linkers in reactions involving dichlorocyclodiphosphazanes potentially gives rise to the possibility of obtaining a mixture of products. Experimentally, the Wright group previously demonstrated the reactions of compound **1.1** with asymmetric organic linkers, such as 2-aminophenol or 2-aminothiophenol, resulted in mixture of *cis/trans* dimeric macrocycles.⁷⁹

However, in our case, only the *trans* macrocycles (**4.4** and **4.5**) were observed and isolated from the reactions of compound **1.1** with asymmetric organic linkers (*i.e.* *p*-hydroxybenzoic acid and 6-hydroxy-2-naphthoic acid). There was no indication of formation of *cis* isomer or any other product in these reactions, as suggested by the presence of pair of doublets recorded on the *in situ* ³¹P-{¹H} NMR spectra. Since there was no evidence of *cis* isomer formed, we attempted to explore synthetic route to generate it.

4.5.1 - Results and discussion for synthesis of tetrameric macrocycle (**4.11**)

Scheme 4.12. Proposed reaction of **1.1** with two equivalents of *p*-hydroxybenzoic acid to obtain acyclic disubstituted cyclodiphosphazane.

We proposed a two-step synthetic procedure to attempt the generation of *cis*-**4.4**. The first step involved addition of diluted THF solution of two equivalents of *p*-

hydroxybenzoic acid and triethylamine into a cooled solution of compound **1.1** dropwisely ($-78\text{ }^{\circ}\text{C}$) (*Scheme 4.12*). As *p*-hydroxybenzoic acid was bifunctional, it was uncertain if the nucleophilic substitution could be controlled to selectively occur on either the hydroxy or acid sites. According to the *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy recorded, it was, in fact, possible. It selectively took place at the acid functionality and resulted in acyclic disubstituted compound **4.4'**, $[(\text{HO}C_6H_4(\text{O})\text{CO})\text{P}(\mu\text{-N}^t\text{Bu})_2]_2$. The chemical shift detected was at δ 172.5 ppm – typical of P-OC(O) substituted cyclodiphosphazanes, **4.1** - **4.3** (in the region of δ 172 – 178 ppm). Despite the tremendous effort to isolate, it has been unsuccessful thus far. Oxidation reactions were attempted to enhance the stability and aid the isolation. However, these efforts were unsuccessful to crystallize any conclusive product thus far.

Scheme 4.13. Second step of proposed synthetic route to generate cis-4.4.

In view of the difficulty, we proceeded to the second step *via in situ* generation of compound **4.4'**. The second equivalent of **1.1** along with triethylamine were added dropwisely into the cooled reaction mixture and left to stir overnight (*Scheme 4.13*). The *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum showed two singlet resonances at δ 180.0 and 150.1 ppm, along with that corresponding to *trans*-**4.4** (doublets centered at δ 143.5 and 140.9 ppm), therefore suggesting the formation of mixture of *trans*-**4.4** and a new product (*Fig. 4.8*).

Figure 4.8. *In situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra of each step for the proposed synthesis of *cis*-**4.4**. (a) Step 1 involving the formation of **4.4'**. (b) Step 2 in which an equivalent of **1.1** and two equivalents of triethylamine were added dropwise.

The reaction solvent was first removed under reduced pressure and hexane was added to extract the new reaction product formed. The hexane solution, contained only the new product, was concentrated and left to crystallize out at 5 °C. Colorless crystals were grown after standing for overnight. The first batch of crystals was dried and characterized by $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy. The $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum showed two singlet resonance signals at δ 179.8 and 150.8 ppm, indicating that the crystals were not *trans* dimeric macrocycle **4.4** but the new product obtained. Hence, the ^1H NMR spectrum, in CDCl_3 , was recorded and found to show three resonance signals at δ 8.11, 7.17 and 1.39 ppm with the integral ratio of 1:1:9. The multinuclear NMR spectroscopic analyses, at this juncture, supported the presumption of successful formation of newly formed product, *cis*-**4.4**.

4.5.2 - X-ray crystallographic study of macrocycle **4.11**

Scheme 4.14. Reaction of **1.1** and *p*-hydroxybenzoic acid to obtain tetrameric macrocycle (**4.11**).

However, a SC-XRD study showed the product to be the tetrameric macrocycle **4.11** rather than the corresponding dimeric *cis*-**4.4'**. The tetrameric macrocycle (**4.11**) was made up of alternating four P_2N_2 units and four $-\text{OC}_6\text{H}_4\text{C}(\text{O})\text{O}-$ units (Scheme 4.14).

Figure 4.9. Molecular structure of tetrameric macrocycle (**4.11**). The tert-butyl groups are shown in wireframe.

Positional disorder was observed in the SC-XRD data collected. However, it was possible to identify the molecular structure to be tetrameric macrocycle **4.11** (Fig. 4.9).

The diffraction data revealed the organic linker (*i.e.* *p*-hydroxybenzoic acid) was bonded in *cis* manner to the P₂N₂ rings. This arrangement was consistent with the detection of two singlet resonance signals on the ³¹P-{¹H} NMR spectroscopy. The selectivity of *cis* over *trans* arrangement observed in **4.11** therefore illustrated the influence of reaction condition on the the reaction outcomes.

The formulation of **4.11** was further supported by high-resolution mass spectroscopy (HRMS), which recorded a molecular ion peak at $m/z = 1361.45$ ([M+1]⁺). Compound **4.11** was the first tetrameric P₂N₂-based macrocycle to be obtained from reacting **1.1** with an asymmetric organic linker, to date.

4.5.3 – ¹H NMR spectroscopic studies of compound **4.11**

Judging from the SC-XRD data collected, it would be expected that the *tert*-butyl groups in **4.11** to be chemically different, resulting in two distinct sets of resonance signals on ¹H NMR spectrum. However, the ¹H NMR spectrum recorded earlier, in CDCl₃, exhibited only one characteristic resonance signal (δ 1.39 ppm) corresponding to *tert*-butyl group. In view of that, another deuterated solvent, specifically toluene-d₈, was used. The ¹H NMR spectrum revealed two characteristic resonance signals corresponding to *tert*-butyl groups at δ 1.33 and 1.24 ppm with the integral ratio of 1:1. This difference observed on the ¹H NMR spectra recorded separately in two deuterated solvents hence indicated the chemical shifts of **4.11** are solvent-dependent.

We carried out variable temperature (VT) ¹H and ³¹P-{¹H} NMR spectroscopic studies for the sample prepared in CDCl₃ to investigate if the chemical shifts were temperature-dependent.

Figure 4.10. Variable temperature (VT) ^1H NMR spectra of **4.11** recorded in CDCl_3 over the range of -55 to 25 $^\circ\text{C}$. (a) Full spectra over δ 8.5 - -1.0 ppm. (b) Zoomed in spectra in the range of δ 1.41 – 1.32 ppm.

The VT NMR spectroscopic studies were conducted over the range of -55 to 25 $^\circ\text{C}$ using Bruker AvanceIII 400 (BBFO probe). There was no observable change on the $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum of **4.11** (δ 179.8 and 150.8 ppm) recorded over the studied temperature range.

On the other hand, the ^1H NMR spectroscopic studies revealed changes to the splitting patterns of the resonance signals over the studied temperature range (Fig. 4.10). The ^1H NMR spectroscopy recorded at room temperature (25 $^\circ\text{C}$), showed only three distinct resonance signals - two signals corresponding to the aromatic protons and the remaining one to the *tert*-butyl groups (bottom-most spectrum on Fig. 4.10a and b). As the temperature was lowered to 15 $^\circ\text{C}$, broadening of the resonance signal corresponding to the *tert*-butyl groups was observed (2nd spectrum from the bottom on Fig. 4.10b). Further lowering of temperature by 10 $^\circ\text{C}$ led to splitting of the singlet resonance signal into broad doublet as illustrated on Fig. 4.10b. The splitting became evident as the temperature was lowered, but it then began to coalesce upon further cooling after -15 $^\circ\text{C}$ and eventually resulted in a broad singlet resonance signal at -45 $^\circ\text{C}$ (Fig. 4.10b).

The splitting and coalescence of the resonance signals serves as a potential explanation for the severe disorder observed for the *tert*-butyl groups in the SC-XRD data collection.

4.6 – Conclusion of the chapter

In this chapter, we demonstrated the successful syntheses of various hybrid macrocycles bearing the elusive P-OC(O) moiety. Further oxidations were carried out on *trans* macrocycle, **4.4**, without breaking macrocyclic arrangement and Arbuzov-type rearrangement was not observed. For the first time, a novel tetrameric P₂N₂ macrocycle was prepared from the reaction of **1.1** with asymmetrical organic linkers. Such tetrameric macrocycle has yet to be reported and hence represents an exciting milestone in creating hybrid inorganic-organic systems.

Chapter 5 – Incorporating Ester Moiety into Cyclophosphazane Frameworks

5.1 – Introduction

Scheme 5.1. Typical reaction scheme of compound **1.1** with monofunctional organic linkers.

Generally, the reactions involving dichlorocyclodiphosph(III)azanes comprised the use of mono- and bi-functional nucleophiles. Most of the nucleophiles used bear no other functional groups that can be employed for further reactions. This lack of functionality on synthesized cyclodiphosphazanes has limited their further applicability (Scheme 5.1).

Scheme 5.2. Representative synthetic route for targeted acyclic cyclodiphosphazanes.

To explore and increase the possible further applicability of cyclodiphosphazanes, functionality that are inert to P-Cl moiety needs to be introduced onto the organic nucleophiles and react with compound **1.1** (Scheme 5.2). Esters are chosen as they can be readily reduced to alcohols or hydrolyzed to carboxylic acids. Hence, there are many possible subsequent reactions after reduction or hydrolysis to alcohols and acids, to further build up on the complexity of the species.

Figure 5.1. General illustration of types of cyclodiphosphazane-based frameworks.

In the last two decades, the most commonly synthesized type of cyclodiphosphazane-based frameworks are type **VI** and **XVII** systems (*Fig. 5.1*).¹⁹ Similarly, there is lack of additional functional group(s) present in type **XVII** cyclodiphosphazanes. This therefore verified the need and justified our interest in introducing ester moiety into cyclodiphosphazane-based frameworks as a mean to increase utility of P₂N₂-based frameworks. In addition, we also identified that type **XI** cyclodiphosphazanes are of limited examples. Hence, we aimed to synthesize an array of cyclodiphosphazane-based frameworks (Type **VI**, **XVII** and **XI**) bearing ester functionality.

Scheme 5.3. Proposed reaction syntheses for functionalized cyclodiphosphazanes.

We first focus and limit the scope of study to syntheses of ester-incorporated type **VI** and **XVII** cyclodiphosphazanes, stemming from the use of compound **1.1** (*Scheme 5.3*). Specifically, we employed both ethyl 4-hydroxybenzoate and methyl 3,5-dihydroxybenzoate as the two organic nucleophiles of interest. Both organic nucleophiles are symmetrical and relatively simple to characterize using ¹H NMR spectroscopy. In the second half of this chapter, we presented the syntheses of type **XI** cyclodiphosphazane-based compounds by reacting methyl 3,5-dihydroxybenzoate with compound **1.2**.

5.2 – Syntheses of acyclic disubstituted cyclodiphosphazanes, [(*p*-OC₆H₄CO₂Et)(E)P(μ -N^{*t*}Bu)]₂ (5.1 – 5.4)

5.2.1 – Results and discussion for compounds 5.1 – 5.4

Scheme 5.4. Synthesis of [(*p*-OC₆H₄CO₂Et)P(μ -N^{*t*}Bu)]₂ (**5.1**) from reacting **1.1** with ethyl 4-hydroxybenzoate.

One equivalent of **1.1** was reacted with two equivalents of ethyl 4-hydroxybenzoate in THF at room temperature to yield acyclic disubstituted cyclodiphosph(III)azane, [(*p*-OC₆H₄CO₂Et)P(μ -N^{*t*}Bu)]₂ (**5.1**) (Scheme 5.4). The reaction afforded a mixture of *cis* and *trans* isomers, as indicated by the presence of two singlet resonance signals on the *in situ* ³¹P-{¹H} NMR spectroscopy (δ 144.2 and 234.4 ppm *cf.* δ 207 ppm for **1.1**). The resultant by-product, triethylammonium chloride, was removed by filtration and the filtrate was concentrated to yield crystalline solid. The first batch of crystalline solid obtained was a mixture of *cis/trans* isomers in the ratio of ~10:1, as determined by ³¹P-{¹H} NMR. This ratio of isomers was further corroborated by ¹H NMR spectroscopy data, with integral ratios of 87:13 measured based in the resonance signals of the aromatic region. Judging from the ³¹P-{¹H} NMR spectroscopy of the second batch of crystalline solid, the crystalline solid was identified as pure *cis* isomer of **5.1** (δ 144.2 ppm *cf.* to that of *cis*-[(*p*-OC₆H₄CN)P(μ -N^{*t*}Bu)]₂ (δ 143.8 ppm)).⁹¹ Despite numerous attempts, diffraction quality single crystals of *cis*-**5.1** were not obtained, and the *trans* isomer has yet to be successfully isolated from the *cis-trans* mixture. However, it is possible to assign the ³¹P-{¹H} NMR chemical shift of δ 234.4 ppm to the *trans* product as it was reported the chemical shift of *trans* isomer to be more downfield shifted as

compared to that of the *cis*.¹⁸⁸ In addition, the ¹H NMR spectroscopy exhibited distinct sets of resonance signals for both *cis* and *trans* isomers of **5.1**. The minor set of resonance signals, recorded for the first batch of crystalline solid, were analyzed and interpreted to be consistent to that of *trans* isomer (see experimental section for the ¹H NMR data).

Scheme 5.5. Oxidation reaction of compound **5.1** with *tert*-butyl hydroperoxide to generate dioxide derivative **5.2**.

Oxidation reactions were carried out in hope to enhance the stability of cyclodiphosphazane towards air and moisture which would be favourable for subsequent hydrolysis or reduction of ester moiety. These oxidations were expected to produce compounds, which are analogous to the acyclic disubstituted cyclodiphosphazanes, [(*p*-OC₆H₄CN)(E)P(μ -N^{*t*}Bu)]₂, reported previously by our group.⁹¹ Compound **5.1** was synthesized *in situ* and THF solution containing *tert*-butyl hydroperoxide was subsequently added dropwise at 0 °C to generate dioxide derivative, [(*p*-OC₆H₄(CO₂Et))(O)P(μ -N^{*t*}Bu)]₂ (**5.2**) (Scheme 5.5). This reaction was performed using traditional solution-based method. As solid oxidants such as *N*-pyridine oxide and *meta*-chloroperoxybenzoic acid (*m*-CPBA) are found to oxidize **1.1** to [Cl(O)P(μ -N^{*t*}Bu)]₂ almost instantaneously upon mixing of the solids, ball milling technique are not necessary for generation of compound **5.2**. The ³¹P-{¹H} NMR spectrum revealed two singlet signals at δ 4.2 and -8.1 ppm, in the range for phosphorus(V) and P=O species – hence supportive of the formation of dioxide species. The reaction mixture was filtered and vacuum-dried to yield white residue. Extraction with hexane and diethyl ether were

performed, and the combined organic layers were evaporated to yield solid **5.2**. The solid compound was characterized by $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy to reveal chemical shift of δ -8.2 ppm which was comparable to that reported for structural analog, *cis*-[μ -2,2'-O(C₁₀H₆)₂O]{(O)P(μ -N^{*t*}Bu)}₂] (δ -7.8 ppm).¹⁸⁹ The ^1H NMR spectrum exhibited resonance signals at δ 8.08, 7.42, 4.39, 1.44 and 1.40 ppm with intensity of 2:2:2:9:3, respectively, indicative of the *para*-substituted benzene ring with an ester moiety.

Scheme 5.6. Orthogonal one-pot one-step mechanochemical syntheses of compounds **5.3** – **5.4**.

The oxidation reactions with elemental sulfur and selenium were conducted using ball milling method to afford the disulfide (**5.3**) and diselenide (**5.4**) derivatives. The reactions were performed with compound **1.1**, ethyl 4-hydroxybenzoate, triethylamine and elemental chalcogen in 1:2:2:3 molar ratios (Scheme 5.6).⁶⁰ The *ex situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy of the reaction crudes exhibited resonance signals at δ 50.3 (minor) and 45.6 (major) ppm, and δ 45.7 (minor) and 39.1 (major) ppm for syntheses of compounds **5.3** and **5.4**, respectively. Only *cis*-**5.3** and both isomers of **5.4** were isolated as single crystals and further characterized by multinuclear NMR spectroscopy, FTIR and HRMS. The $^{31}\text{P}\{-^1\text{H}\}$ NMR chemical shifts for both crystals of **5.4** were recorded and were consistent with initial prediction of the *trans* isomer having downfield chemical shifts as compared to that of *cis* isomer.

All the ^1H and ^{13}C NMR spectra for the three oxidized cyclodiphosphazanes showed the characteristic resonance signals corresponding to ester and *para*-substituted benzene moieties. The FTIR absorption spectra detected the characteristic absorption bands in the region of $1730 - 1715\text{ cm}^{-1}$ corresponding to the ester moiety, and the absence of O-H absorption band suggested the completion of all the reactions to obtain **5.1** – **5.4**. The air and hydrolytic stabilities studies were conducted over the span of 12 months and 1 month, respectively, to conclude that compounds **5.2** – **5.4** are air and water stable.

5.2.2 – X-ray crystallographic studies for compounds **5.3** – **5.4**

Diffraction quality single crystals of *cis*-**5.3** and both *cis* and *trans* isomers of **5.4** were successfully isolated by recrystallization. All three compounds crystallized in triclinic crystal systems and the molecular structures were illustrated as Fig. 5.2 - 5.3. The single crystals of *cis*-**5.3** were obtained from saturated methanol solution while, the *trans* isomer has yet to be isolated. The reaction mixture containing compound **5.4** was first filtered and the filtrate was evaporated to dryness under reduced pressure. The isomers were then separated by solvent extraction using toluene to obtain the *cis* isomer while the *trans* form was isolated by recrystallization of toluene residue in THF.

Figure 5.2. Single crystal X-ray structure of *cis*-**5.3**. The tert-butyl groups are drawn as wireframes. Thermal ellipsoids with 50 % probability at 100 K. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å): P1-S1 1.9104(5), P2-S2 1.9115(5), P1-N1 1.6737(12), P1-N2 1.6878(11), P2-N1 1.6786(11), P2-N2 1.6810(12), P1-O1 1.5994(10), P2-O2 1.6045(11); Selected bond angles (°): N1-P1-N2 84.71 (6), N1-P2-N2 84.77(6), P1-N1-P2 95.32(6), P1-N2-P2 94.71(6), N1-P1-O1 101.46(6), N2-P2-O2 109.26(5), O1-P1-S1 114.28(4), O2-P2-S2 107.37(4).

Figure 5.3. Single crystal X-ray structure of (a) *cis*-**5.4** (left) and (b) *trans*-**5.4** (right). The *tert*-butyl groups are drawn as wireframes. Thermal ellipsoids with 50 % probability at 100 and 103 K respectively. Hydrogen atoms are omitted for clarity. *Cis*-**5.4**: Selected bond lengths (Å): P1-Se1 2.0595(5), P2-Se2 2.0618(6), P1-N1 1.6896(18), P1-N2 1.6764(17), P2-N1 1.6836(17), P2-N2 1.6781(17), P1-O1 1.6032(15), P2-O4 1.6035(14); Selected bond angles (°): N1-P1-N2 84.44(8), N1-P2-N2 84.57(9), P1-N1-P2 95.01(9), P1-N2-P2 95.71(9), N1-P1-O1 107.96(8), N2-P2-O4 109.80(8), O1-P1-Se1 113.94(6), O4-P2-Se2 107.61(6); *Trans*-**5.4**: Selected bond lengths (Å): P1-Se1 2.0573(4), P1-N1 1.680(3), P1-N2 1.6736(12), P1-N1 1.6827(12), P1-O1 1.6120(11) Selected bond angles (°): N1-P1-N1 84.32(6), P1-N1-P1 95.68(6), N1-P1-Se1 122.15(5), N1-P1-Se1 122.49(4), O1-P1-Se1 112.81(4), N1-P1-O1 105.08(6).

The exocyclic oxygen atoms in both *cis*-isomers of compounds **5.3** and **5.4** were oriented in *exo*, *endo* manner (Fig. 5.2 and 5.3a), commonly found in such acyclic disubstituted compounds (e.g., **3.6** and **3.7**).

The average P=S bond distance in *cis*-**5.3** was calculated to be 1.911(1) Å, comparable to that of the structural analogs, [(Me₃SiO)(S)P(μ-N^{*t*}Bu)]₂ and [(MeO)(S)P(μ-NPh)]₂ (1.914(7) and 1.898(1) Å respectively).^{185,190} The P=Se distances in both isomers of **5.4** were in the range of 2.057(1) – 2.062(1) Å, similar to that in cyclodiphosph(V)azane compound, *cis*-[μ-2,2'-O(C₁₀H₆)₂O]{(Se)P(μ-N^{*t*}Bu)}₂ (2.049 – 2.061 Å).¹⁸⁶ The endocyclic P-N bond distances (1.674(1) – 1.690(2) Å) in these three crystallized cyclodiphosph(V)azanes were in the typical range of endocyclic P-N bond distances for reported analogs, [(2-OCH₂C₅H₄N)(S)P(μ-N^{*t*}Bu)]₂ (1.669(3) – 1.679(3) Å) and [(μ-O(C₁₀H₆)₂O)(Se)P(μ-N^{*t*}Bu)]₂ (1.667(3) – 1.681(3) Å).^{173,186} The mean exocyclic P-O bond distances in *cis*-**5.3**, *cis*-**5.4** and *trans*-**5.4** were found to be 1.602(2), 1.603(2) and 1.612(1) Å, respectively, which were within the range of typical P-O bond in cyclodiphosph(V)azane derivatives, [(Me₃SiO)(S)P(μ-N^{*t*}Bu)]₂ and *cis*-[μ-2,2'-O(C₁₀H₆)₂O]{(Se)P(μ-N^{*t*}Bu)}₂ (1.540(12) and 1.602(3) Å, respectively).^{185,186}

The average S-P-O bond angles in compound **5.3** were calculated to be $110.8(1)^\circ$, comparable to that in similar cyclodiphosph(V)azane species, $[(2\text{-OCH}_2\text{C}_5\text{H}_4\text{N})(\text{S})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ ($112.5(1)^\circ$).¹⁷³ The mean endocyclic N-P-N and P-N-P bond angles within **5.3** were $84.7(1)$ and $95.0(1)^\circ$, respectively. These angles were in good agreement with sulfur-oxidized cyclodiphosphazane, $[(2\text{-OCH}_2\text{C}_5\text{H}_4\text{N})(\text{S})\text{P}(\mu\text{-N}^t\text{Bu})]_2$ ($84.1(1)$ and $95.7(2)^\circ$, respectively).¹⁷³ The Se-P-O bond angles in the *cis* and *trans* isomers of **5.4** are $107.6(1)$ - $113.9(1)^\circ$ and $112.8(1)^\circ$ respectively, which were similar to that in *cis*- $[\{\mu\text{-}2,2'\text{-O}(\text{C}_{10}\text{H}_6)_2\text{O}\}\{(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})\}_2]$ ($110.0(1)^\circ$).¹⁸⁶ The endocyclic N-P-N and P-N-P bond angles were $84.6(1)$ – $84.9(1)^\circ$ and $95.0(1)$ – $95.7(1)^\circ$ respectively for *cis*-**5.4**. While for *trans*-**5.4**, it was $84.3(1)$ and $95.7(1)^\circ$, respectively. These bond angles were comparable to that in cyclodiphosph(V)azane, *cis*- $[\{\mu\text{-}2,2'\text{-O}(\text{C}_{10}\text{H}_6)_2\text{O}\}\{(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})\}_2]$ ($84.9(2)$ and $95.1(2)^\circ$ respectively).¹⁸⁶

5.3 – Syntheses of dimeric macrocycles with ester moiety, [(E)P(μ -N^tBu)₂P(E)(μ -3,5-OC₆H₃(CO₂Me)O)]₂ (5.5 – 5.8)

5.3.1 – Prior work reported

Balakrishna and co-workers have previously reported the isolation of both dimeric (major) and tetrameric (minor) macrocycles from the reaction of compound **1.1** and 1,3-dihydroxybenzene.⁵⁶ Hence, we carried out the reaction of **1.1** with methyl 3,5-dihydroxybenzoate and expected to similarly obtain a mixture of reaction products.

5.3.2 – Results and discussion for syntheses of compounds 5.5 – 5.8

Scheme 5.7. Formation of macrocyclic arrangement from the reaction of compound **1.1** and methyl 3,5-dihydroxybenzoate.

The reaction of one equivalent of **1.1** and equimolar amount of methyl 3,5-dihydroxybenzoate was carried out in THF at room temperature (Scheme 5.7). The *in situ* ³¹P-{¹H} NMR spectrum revealed three singlet resonance signals, similar to that reported by Balakrishna *et al.* for the analogous reaction of **1.1** and 1,3-dihydroxybenzene. The Balakrishna group documented to yield dimeric and tetrameric macrocycles from the reaction in which the ³¹P-{¹H} NMR chemical shifts recorded were δ 131.5 and 146.0 ppm, respectively.⁵⁶ In our case, the three singlet chemical shifts recorded were δ 133.2, 140.0 and 143.1 ppm, in which the signals at δ 133.2 and 143.1 ppm were relatively close to those reported by Balakrishna *et al.*, hence suggesting the

possible formation of dimeric and tetrameric ester-incorporated cyclodiphosphazane-based macrocycles in the reaction.

After several workup steps, diffraction quality single crystals were obtained and found to be the desired dimeric ester-incorporated macrocycle (**5.5**). While attempts to isolate the other products, associated with the two $^{31}\text{P}\{-^1\text{H}\}$ singlet resonance signals, by recrystallization were unsuccessful thus far. The Balakrishna group strategized and separated the mixture of macrocyclic arrangements by column chromatography with *n*-hexanes and dichloromethane under nitrogen atmosphere, followed by recrystallization from toluene to successfully obtain pure crystalline dimeric and tetrameric compounds from the respective fractions.⁵⁶ Adopting such a strategy in our case did not result in any positive outcomes to date.

*Scheme 5.8. Reaction scheme for oxidation reactions of macrocyclic arrangement **5.5** to phosphorus(V) derivatives **5.6** - **5.8**.*

Moving on, oxidation reactions were carried out on the synthesized dimeric macrocycle (**5.5**), using solution-based methods with the appropriate oxidising agents (*Scheme 5.8*). These oxidation reactions were performed to generate the oxidized derivatives (**5.6** - **5.8**), which we hoped to have enhance air- and moisture-stability as compared to its parent compound **5.5**.

The oxidation reaction with *tert*-butyl hydroperoxide was carried out in THF at 0 °C and left to stir at room temperature overnight, resulting in formation of tetra-oxidized derivative (**5.6**). While, the syntheses of the sulfide and selenide derivatives (**5.7** and **5.8**

respectively) were performed by refluxing the toluene mixture of compound **5.5** and the corresponding chalcogen elements. All three oxidation reactions proceeded to give phosphorus(V) species, as indicated by the *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra recorded. The *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra showed major peaks at δ -12.1, 40.4 and 33.1 ppm for the oxidation reactions to **5.6**, **5.7** and **5.8**, respectively. The chemical shifts recorded for generation of compounds **5.6** and **5.8** were comparable to those reported for structural analogs, $[(\text{O})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{O})(\mu\text{-1,3-OC}_6\text{H}_4\text{O})]_2$ (δ -11.9 ppm) and $[(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{Se})(\mu\text{-1,3-OC}_6\text{H}_4\text{O})]_2$ (δ 32.7 ppm), respectively.⁵⁶ The isolation of tetra-oxide **5.6** was thus far unsuccessful *via* recrystallization. Several solvents such as THF, toluene, diethyl ether, acetone and methanol were used to recrystallize the product from the reaction mixture, but to no avail. Compounds **5.7** and **5.8** were successfully isolated in relatively pure form by repeated extractions with different organic solvents and then further purified by recrystallization. The diffraction quality single crystals of tetra-sulfide **5.7** were obtained from recrystallization in chloroform and benzene mixture. Diffraction quality single crystals of **5.8** have yet to be obtained.

The ^1H NMR spectroscopy recorded for compounds **5.7** and **5.8** exhibited characteristic resonance signals corresponding to ester moiety at δ 3.32 and 3.94 ppm, respectively, supporting the presence of ester groups. The FTIR spectroscopic data for compound **5.8** revealed characteristic C=O absorption stretching at ν = 1724 and 1589 cm^{-1} , indicative of the presence of carboxyl moiety. The formulation of **5.8** has been further confirmed from the high-resolution mass spectroscopy (HRMS), which showed a molecular ion peak at m/z = 1060.92 ($[\text{M}+1]^+$).

These compounds were tested *via* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectroscopy from time to time to show no sign of decompositions despite exposure to air and moisture. Therefore, it

suggested that the oxidized macrocyclic derivatives were considerably stable to the normal atmosphere.

5.3.3 – X-ray crystallographic studies for compounds 5.5 and 5.7

Single crystals of compounds **5.5** and **5.7** were successfully obtained from recrystallization in THF and, chloroform with drops of benzene, respectively. Both compounds crystallized in monoclinic crystal system with four and two molecules in its unit cell, respectively.

5.5

5.7

Figure 5.4. ORTEP drawing (left), and sideview (right) of molecular structure of compounds **5.5** (top) and **5.7** (bottom). The tert-butyl groups are drawn as wireframes. Thermal ellipsoids with 50 % probability at 103 and 100 K respectively. Hydrogen atoms are omitted for **5.5** while hydrogen atoms and benzene solvate molecules are omitted for **5.7** for clarity. Compound **5.5**: Selected bond lengths (Å): P1-N1 1.705(2), P2-N1 1.692(2), P2-N2 1.713(2), P1-N2 1.717(2), P1-O1 1.6532(17), P2-O2 1.6676(16), C9-O1 1.384(3), C11-O2 1.381(3); Selected bond angles (°): N1-P1-N2 80.44(9), N1-P2-N2 80.93(10), P1-N1-P2 98.78(10), P1-N2-P2 97.53(10), O1-P1-N1 109.56(10), O1-P1-N2 108.59(9), O2-P2-N1 99.77(9), O2-P2-N2 103.06(9); Compound **5.7**: Selected bond lengths (Å): P1-N1 1.6813(10), P1-N2 1.6802(10), P2-N1 1.6846(10), P2-N2 1.6743(10), P1-O1 1.6078(9), P2-O2 1.6038(9), P1-S1 1.9119(4), P2-S2 1.9055(4); Selected bond angles (°): N1-P1-N2 84.35(5), N1-P2-N2 84.43(5), P1-N1-P2 94.86(5), P1-N2-P2 95.28(5), O1-P1-N1 109.83(5), O2-P2-N2 102.43(5)..

The aromatic rings in compound **5.5** were almost co-planar and the P₂N₂ rings were eclipsed to each other (*Fig. 5.4*). In comparison, the aromatic rings in compound **5.7** were almost parallel to each other (*Fig. 5.4*). The exocyclic oxygen atoms in both compounds were oriented in *exo*, *endo* manner, resulting in formations of elongated cavities with the distances between the diagonal oxygen atoms to be 8.096 and 3.702 Å, and, 7.888 and 3.913 Å for **5.5** and **5.7**, respectively (*cf.* that in [P(μ -N'Bu)₂P(μ -1,3-OC₆H₄O)]₂ (7.838 and 3.827 Å)).⁵⁶ The distance between the centroids of the two P₂N₂ rings in **5.5** (6.949 Å) was found to be comparable to that in structural analog, [P(μ -N'Bu)₂P(μ -1,3-OC₆H₄O)]₂ (6.925 Å).⁵⁶ While that in **5.7** (6.806 Å) was relatively shorter and so was the cavity. The mean P-O bond lengths were measured to be 1.661(2) and 1.606(1) Å for **5.5** and **5.7**, respectively, suggesting that the oxidation had significantly shortened the P-O bonds. The average endocyclic P-N bond distances were calculated to be 1.701(2) and 1.680(1) Å for **5.5** and **5.7**, respectively. The P-N-P bond angles were in the range of 97.5(1) - 97.8(1)° and 94.9(1) - 95.3(1)° for **5.5** and **5.7** respectively. These parameters were in good agreement with that in similar dimeric macrocycles, [P(μ -N'Bu)₂P(μ -1,3-OC₆H₄O)]₂ (endocyclic P-N bond distances: 1.697(4) - 1.724(4) Å and P-N-P bond angles: 97.6(2) - 97.9(2)°) and [(Se)P(μ -N'Bu)₂P(Se)(μ -1,3-OC₆H₄O)]₂ (mean endocyclic P-N bond distance: 1.685(1) Å and average P-N-P bond angle: 95.1(1)°).⁵⁶

Figure 5.5. Packing network of compound **5.7**. The tert-butyl groups on the P_2N_2 rings and the ester moiety are omitted for clarity.

It was found that there were two benzene solvate molecules co-crystallized with one molecule of the compound **5.7** in its crystal structure (*Fig. 5.5*). One of the two benzene solvate molecules was found to interact with one of the selenium atoms on the molecule of **5.7** via one of the its six C-H moieties. The opposite C-H group of that same benzene molecule also have a similar interaction with another selenium atom on another neighbouring molecule of the compound **5.7**.

5.4 – Syntheses of bis(cyclodiphosphazane) frameworks [(^tBuHN)(E)P(μ-N^tBu)₂P(E)]₂(μ-3,5-OC₆H₃(CO₂Me)O) (5.9 – 5.12)

5.4.1 – Prior work reported

Scheme 5.9. Synthetic routes of reported bis(cyclodiphosphazane) frameworks.^{56,82,83}

In this context, cyclodiphosphazanes of type **XI**, [(^tBuHN)P(μ-N^tBu)₂P]₂X where X = bridging groups, are referred to as bis(cyclodiphosphazane) compounds (Fig. 5.1). The reported examples of these cyclodiphosphazanes are limited even up to today. Some known examples are the ones obtained from the reaction of two equivalents of compound **1.2** with an equivalent of 1,3-dihydroxybenzene, 2-iodo-1,3-dihydroxybenzene or ethylene glycol (Scheme 5.9).^{56,82,83}

Figure 5.6. Examples of bis(cyclodiphosphazane) compounds coordination with metal complexes.⁸²

Balakrishna *et al.* reported on the utilization of the bis(cyclodiphosphazane) compound, [(^tBuHN)P(μ-N^tBu)₂P]₂(μ-OCH₂CH₂O), as neutral ligands for binding to metal centers,

such as Rh(I), Au(I) and Pd(II). Depending on the metal centers used, homometallic and heterometallic complexes can be obtained (*Fig. 5.6*).⁸² The group then carried out analogous reaction with 2-iodo-1,3-dihydroxybenzene to yield derivative bearing iodo-substituent, $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}]_2(\mu\text{-2-I-1,3-OC}_6\text{H}_3\text{O})$ which was then employed as a PCP pincer-type ligand for coordination to metal centers *via* oxidative addition (*Scheme 5.10*).⁸³

Scheme 5.10. Oxidative addition reactions between $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}]_2(\mu\text{-2-I-1,3-OC}_6\text{H}_3\text{O})$ and metal centers such as Ni(0), Pd(0) and Pt(0).

To date, the applicability of these compounds still remains limited to metal complexation. Hence, it prompted us to further extend the idea of introducing ester moiety to these bis(cyclodiphosphazane) compounds. The ester moiety can subsequently be hydrolyzed or reduced to generate reactive functionality for further reactions. For instance, to generate macromolecular compounds or heterometallic metal complexes. Examples of each proposed idea are shown in *Fig. 5.7*.

Figure 5.7. Examples of (a) macromolecular compound and (b) multinuclear heterometallic complex using the same cyclodiphosphazane ligand as proposed ideas. M^1 represents soft metal centers such as Au(I) and Pd(II) while M^2 represents oxophilic metal e.g., titanium, silicon and lanthanides.

5.4.2 – Results and discussion for syntheses of compounds 5.9 – 5.12

Scheme 5.11. Reaction scheme of compound **1.2** with methyl 3,5-dihydroxybenzoate to obtain bis(cyclodiphosphazane) compound (**5.9**).

The reaction of two equivalents of **1.2** and one equivalent of methyl 3,5-dihydroxybenzoate to generate bis(cyclodiphosphazane) compound (**5.9**), [(^tBuHN)P(μ-N^tBu)₂P]₂(μ-3,5-OC₆H₃(CO₂Me)O) with ester functionality incorporated (Scheme 5.11). The *in situ* ³¹P-{¹H} NMR spectrum revealed two distinct sets of doublets centered at δ 131.1 and 101.6 ppm (²J_{P-P} = 9.7 Hz), indicating the quantitative conversion of **1.2** to the desired compound, **5.9**. The THF solution was evaporated to dryness and the product was extracted with toluene. The resulting toluene solution was then concentrated and left to crystallize, yielding colorless crystals of compound **5.9**. The ¹H NMR spectroscopy recorded resonance signals at δ 7.55, 6.95, 3.89, 2.26, 1.34 and 1.08 ppm with the intensity of 2:1:3:2:36:18, indicative of the presence of the ester group and further supported the successful formation of **5.9**. The absence of O-H stretching absorption band (ν = 3300 cm⁻¹) and the presence of sharp N-H stretching and carboxyl stretching absorption band at ν = 3337 and 1730 cm⁻¹, respectively, on the FTIR spectra confirmed the complete conversion of monochlorocyclodiphosphazane **1.2** to targeted bis(cyclodiphosphazane) compound **5.9**.

Scheme 5.12. Oxidation of compound **5.9** to oxidized derivatives, $[(^t\text{BuHN})(\text{E})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{E})]_2(\mu\text{-3,5-OC}_6\text{H}_3(\text{CO}_2\text{Me})\text{O})$ (**5.10** – **5.12**).

The oxidation reactions were conducted using established solution-based methods. Tetra-oxidized derivatives (**5.10** – **5.12**) were prepared by oxidizing compound **5.9** with either four equivalents of *tert*-butyl hydroperoxide at 0 °C or refluxing with four equivalents of elemental chalcogen (Scheme 5.12).

The oxidation reaction to synthesize the tetra-oxide species (**5.10**) resulted in a complex mixture of products, suggested by the *in situ* ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy. All attempts to obtain diffraction quality single crystals of **5.10** were unsuccessful thus far. However, **5.10** was isolated as pure solid and characterized by ^{31}P - $\{^1\text{H}\}$ and ^1H NMR spectroscopy studies. The ^{31}P - $\{^1\text{H}\}$ NMR spectrum revealed two singlet resonance signals at δ -4.1 and -4.2 ppm, typical of P=O moiety signals. The ^1H NMR data further supported the successful formation of **5.10** with resonance signals recorded at δ 7.79, 7.67, 3.94, 2.48, 1.46 and 1.43 ppm - consistent to the proposed structure of desired cyclodiphosphazane-based compound (**5.10**).

In the cases of sulfur and selenium oxidations, both *in situ* ^{31}P - $\{^1\text{H}\}$ NMR spectra exhibited two sets of expected resonance signals, suggesting the successful formations of desired tetra-sulfide and tetra-selenide derivatives (**5.11** and **5.12**). For the synthesis of tetra-sulfide **5.11**, the *in situ* ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy illustrated only two distinct sets of doublets centered at δ 43.8 and 39.8 ppm with coupling constant of 27.5 Hz ($^2J_{\text{P-P}}$) and 29.2 Hz ($^2J_{\text{P-P}}$) respectively, suggesting quantitative conversion of compounds **5.9**

to **5.11**. The ^1H NMR spectrum of the crystalline **5.11** isolated showed resonance signals at δ 7.71, 7.38, 3.94, 3.18, 1.67 and 1.47 ppm with the signal intensities of 2:1:3:2:36:18. While for compound **5.12**, the *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum recorded two sets of doublets centered at δ 42.1 and 26.7 ppm with ^{77}Se satellites observed ($^2J_{\text{P-P}} = 13.0$ Hz and $^1J_{\text{P-Se}} = 967.1$ and 884.5 Hz for signals corresponding to inner P and outer P atoms, respectively). The ^1H NMR spectrum showed corresponding resonance signals at δ 7.69, 7.38, 3.93, 3.56, 1.74 and 1.51 ppm with the signal intensities of 2:1:3:2:36:18. Both the ^1H NMR data of tetra-sulfide (**5.11**) and tetra-selenide (**5.12**) supported the successful formation of the desired compounds with the substituted aromatic rings, ester and *tert*-butyl groups remaining intact throughout the oxidation reactions. The presence of the ester groups in the tetra-oxidized compounds was further confirmed by the resonance signals recorded at δ 165.5 ppm on the ^{13}C NMR spectra of both compounds.

5.4.3 – X-ray crystallographic studies for compounds 5.9, 5.11 and 5.12

Despite numerous attempts, recrystallization of compound **5.10** to obtain diffraction quality single crystals was still unsuccessful. While the other three bis(cyclodiphosphazane) compounds (**5.9**, **5.11** and **5.12**) were recrystallized successfully and the solid-state structures were characterized by SC-XRD and are shown *vide infra*.

Figure 5.8. (a) ORTEP drawing of the molecular structure of compound **5.9**. Tert-butyl groups are shown in wireframes. Thermal ellipsoids with 50 % probability at 103 K. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å): P1-N1 1.6542(18), P1-N2 1.7331(18), P1-N3 1.7443(18), P2-N2 1.7000(19), P2-N3 1.7040(18), P3-N4 1.6967(18), P3-N5 1.6965(17), P4-N4 1.7362(18), P4-N5 1.7474(17), P4-N6 1.6516(18), P2-O1 1.6853(15), P3-O4 1.6874(15), C13-O1 1.387(2), C15-O4 1.383(2); Selected bond angles (°): N1-P1-N2 103.57(9), N1-P1-N3 106.15(9), N6-P4-N4 104.27(9), N6-P4-N5 106.54(9), P1-N2-P2 98.77(9), P1-N3-P2 98.18(9), P3-N4-P4 98.38(9), P3-N5-P4 97.95(9), N2-P1-N3 79.93(8), N2-P2-N3 82.02(9), N5-P3-N4 82.43(8), N4-P4-N5 79.85(8), O1-P2-N2 104.79(8), O1-P2-N3 104.21(8), O4-P3-N5 104.47(8), O4-P3-N4 104.92(8); (b) 'S-shaped' backbone of compound **5.9** with hydrogen atoms and tert-butyl groups omitted for clarity.

Diffraction quality single crystals of compound **5.9** were obtained from recrystallization in mixture of THF/toluene (Fig. 5.8). It was observed that in the crystal structure of **5.9**, the exocyclic N-H protons interacted with the aromatic ring *via* weak N-H $\cdots\pi$ interactions (*i.e.* the average distance between the N-H proton to the centroid of the aromatic ring: 2.544 Å *cf.* mean distance between the N-H $\cdots\pi$ interactions in organometallic complexes: 2.71(1) Å).¹⁹¹ This was likely the reason for the formation of 'S-shaped' conformation observed in **5.9** (Fig. 5.8b). The 'S-shaped' arrangement was also seen in the solid-state structure of analog, [(^tBuHN)P(μ -N^tBu)]₂(μ -1,3-OC₆H₄O), reported by Balakrishna *et al.*⁵⁶ Normally, the endocyclic P-N bond where

the phosphorus atoms are attached to exocyclic nitrogen substituents are longer than that of phosphorus attaching to exocyclic oxo-, alkoxo-, aryloxo- substituents.^{53,54} It was observed, in compound **5.9**, indeed the average endocyclic P(aryloxo)-N bond distance was calculated to be 1.699(2) Å while that of P(amino)-N bond distance was 1.740(2) Å. The average exocyclic P-N bond distance was found to be 1.653(2) Å, comparable with that of the structural analogs, [(^tBuHN)P(μ -N'^tBu)]₂(μ -1,3-OC₆H₄O) and [(^tBuHN)P(μ -N'^tBu)₂P]₂(μ -OCH₂CH₂O) (1.648(2) and 1.662(2) Å, respectively).^{56,82} The mean P-O bond length was 1.686(2) Å and the O-P-N bond angles measured were in the range of 104.2(1) – 104.9(1)°. These two parameters were in accordance with that observed in *cis*-[(F₅C₆O)P(μ -N'^tBu)]₂ and *cis*-[(*o*-OC₆H₄PPh₂)P(μ -N'^tBu)]₂ (mean P-O bond distances: 1.685 and 1.668(3) Å, respectively),^{16,178} and that of [(^tBuHN)P(μ -N'^tBu)₂P]₂(μ -OCH₂CH₂O) (O-P-N bond angles: 105.7(1) – 106.7(1)°).¹¹

Figure 5.9. (a) ORTEP drawing of the molecular structure of compound **5.11**. Tert-butyl groups are shown in wireframes. Thermal ellipsoids with 25 % probability at 103 K. Hydrogen atoms and toluene solvate molecules are omitted for clarity. Selected bond lengths (Å): P1-S1 1.925(2), P4-S4 1.928(2), P2-S2 1.914(2), P3-S3 1.911(2), P1-N1 1.617(5), P4-N6 1.629(5), P1-N2 1.702(5), P1-N3 1.707(5), P2-N2 1.667(4), P2-N3 1.669(5), P3-N4 1.667(4), P3-N5 1.647(4), P4-N4 1.692(4), P4-N5 1.710(4), P2-O1 1.607(3), P3-O2 1.606(3); Selected bond angles (°): N1-P1-N2 113.0(2), N1-P1-N3 113.2(2), N4-P4-N6 112.0(2), N5-P4-N6 113.8(2), P1-N2-P2 95.1(2), P1-N3-P2 94.9(2), P3-N4-P4 95.8(2), P3-N5-P4 95.9(2), O1-P2-N3 107.7(2), O1-P2-N2 103.6(2), O2-P3-N4 102.7(2), O2-P3-N5 106.9(2), N1-P1-S1 108.89(18), N6-P4-S4 108.84(18), O2-P3-S3 111.89(15), O1-P2-S2 112.18(15); (b) Backbone illustration of compound **5.11**. The tert-butyl groups and hydrogen atoms are omitted for clarity.

Diffraction quality single crystals of **5.11** were obtained from recrystallization in mixture of hexane/toluene and characterized by SC-XRD (Fig. 5.9). The sulfur atoms were in *cis* arrangements with respect to each P₂N₂ rings. The average P=S bond

distance was determined to be 1.920(2) Å, which was consistent with sulfur-oxidized cyclodiphosphazane-based compounds, [(^tBuHN)(S)P(μ -N^tBu)₂P(S)(*o*-OC₆H₄PPh₂)] and [(^tBuHN)(S)P(μ -N^tBu)]₂ (1.925(1) and 1.925(2) Å, respectively).^{16,93} The exocyclic P-N (1.617(5) – 1.629(5) Å) and P-O (1.607(3) – 1.606(3) Å) bond distances in **5.11** were found to be similar of those observed in sulfur-oxidized cyclodiphosphazane, [(^tBuHN)(S)P(μ -N^tBu)₂P(S)(*o*-OC₆H₄PPh₂)] (1.624(1) and 1.617(1) Å, respectively).¹⁶ It was observed that the O-P-N bond angles in **5.11** spanned over a wider range (102.7(2) – 107.7(2)°) as compared to that found in **5.9** (104.2(1) – 104.9(1)°).

Figure 5.10. (a) ORTEP drawing of the molecular structure of compound **5.12**. Tert-butyl groups are shown in wireframes. Thermal ellipsoids with 50 % probability at 103 K. Hydrogen atoms and toluene solvate molecules are omitted for clarity. Selected bond lengths (Å): P1-Se1 2.0592(9), P2-Se2 2.0805(9), P3-Se3 2.0694(10), P4-Se4 2.0893(10), P1-N1 1.672(3), P1-N2 1.673(3), P2-N1 1.689(3), P2-N2 1.691(3), P2-N3 1.631(3), P3-N4 1.669(3), P3-N5 1.673(3), P4-N4 1.704(3), P4-N5 1.698(3), P4-N6 1.626(3), P1-O1 1.622(2), P3-O2 1.607(2), C13-O1 1.389(4), C15-O2 1.400(4); Selected bond angles (°): N1-P1-N2 84.95(14), N1-P2-N2 83.85(13), N4-P3-N5 84.91(14), N4-P4-N5 83.05(14), N3-P2-N1 111.59(15), N3-P2-N2 111.71(15), N6-P4-N5 112.83(15), N6-P4-N4 113.85(16), P1-N1-P2 95.54(14), P1-N2-P2 95.41(14), P3-N4-P4 95.63(15), P3-N5-P4 95.72(14), O1-P1-N1 105.54(14), O1-P1-N2 104.04(13), O2-P3-N4 101.01(14), O2-P3-N5 109.54(14), N3-P2-Se2 110.01(11), N6-P4-Se4 108.60(11), N1-P1-Se1 122.75(10), N2-P1-Se1 123.01(10), N1-P2-Se2 118.59(10), N2-P2-Se2 118.88(11), N4-P3-Se3 124.22(11), N5-P3-Se3 120.48(11), N5-P4-Se4 118.78(11), N4-P4-Se4 118.02(11); (b) Backbone illustration of compound **5.12**. The tert-butyl groups and hydrogen atoms are omitted for clarity.

Diffraction quality single crystals of compound **5.12** were isolated from recrystallization in toluene and were characterized by SC-XRD. The molecular structure of tetra-selenide **5.12** is illustrated as shown in Fig. 5.10. The selenium atoms were found to be in *cis* arrangements, similar to that observed for the sulfide analog (**5.11**). The average P=Se

bond distance was calculated to be 2.075(1) Å, similar to that found in cyclodiphosphazane selenide derivatives, [(*t*BuHN)(Se)P(μ -N'*t*Bu)]₂ (mean P(amino)-Se: 2.074(1) Å) and *cis*-[(Me₃NCH₂CH₂O)(Se)P(μ -N'*t*Bu)]₂(I)₂ (P(aryloxy)-Se: 2.067(1) – 2.074(1) Å).^{172,174} The endocyclic P-N bond distances were in the range of 1.669(3) – 1.704(3) Å and the average exocyclic P-N and P-O bond distances were found to be 1.629(3) and 1.615(2) Å, respectively. The endocyclic N-P-N and P-N-P bond angles were 83.0(1) – 85.0(1)° and 95.4(1) – 95.8(2)°, respectively, which were comparable to those reported in structural analog, [(*t*BuHN)(Se)P(μ -N'*t*Bu)₂P(Se)]₂(μ -OCH₂CH₂O) (82.9(1) – 84.8(1)° and 95.0(1) – 96.2(1)°, respectively).⁸²

Figure 5.11. Comparison of the backbones of the solid-state structures of compounds 5.9 (Top), 5.11 and 5.12 (Bottom).

Moving on, it was worth pointing out that the backbones of bis(cyclodiphosphazane) compounds were observed to undergo significant topological changes upon oxidation reactions. Comparing the three solid-state structures of **5.9**, **5.11** and **5.12**, the ‘S-shaped’ backbone seen gradually flattened out upon oxidation (*Fig. 5.11*). This difference could be attributed to the size of the chalcogen atoms introduced onto the phosphorus atoms.

5.5 - Conclusion of the chapter

An array of cyclodiphosphazane-based frameworks (**5.1** – **5.12**) bearing ester functionality had been successfully synthesized and characterized. These compounds are subjected to further functionalization upon simple hydrolysis or reduction of the ester moiety, and these studies are currently underway.

Chapter 6 – Tris(Cyclodiphosphazane) and Beyond Macrocycles

6.1 - Introduction

In the past chapters, we focused on using either mono- or bi-functional organic compounds to react with dichlorocyclodiphosphazane, $[\text{ClP}(\mu\text{-N}^t\text{Bu})]_2$ (**1.1**), or monochlorocyclodiphosphazane, $[\text{ClP}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{NH}^t\text{Bu})]$ (**1.2**), to produce a variety of cyclodiphosphazane derivatives. For this chapter, we explored with the use of multifunctional organic linkers to generate new family of P_2N_2 -based compounds.

Scheme 6.1. Synthetic scheme of bis(cyclodiphosphazane) compounds.^{56,83}

As illustrated in *Chapter 5*, the bis(cyclodiphosphazane) frameworks, bridged by aromatic bifunctional organic linkers, were obtained from the reactions of compound **1.2** with half-molar amounts of bifunctional organic linkers (Scheme 6.1).^{56,83}

Figure 6.1. Molecular structures of reported examples.^{82,192} The tert-butyl groups are drawn as wireframes and the hydrogen atoms are omitted for clarity.

The replacement of aromatic bridge to alkoxy bridge had significant effect on the structural aspect of the resulting bis(cyclodiphosphazane) compounds. The single crystal

X-ray structure of $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}]_2(\mu\text{-(OCH}_2\text{C(C}_2\text{H}_5)_2)_2)$ revealed its to be “U-shaped”, while $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}]_2(\mu\text{-1,3-OC}_6\text{H}_4\text{O})$ illustrated a folded, “S-shaped” backbone (Fig. 6.1).^{82,192}

Scheme 6.2. Reaction of **1.2** with tetrahydroxymethylmethane to obtain tetrameric acyclic cyclodiphosphazane compound.¹⁹²

Other than these bis(cyclodiphosphazane) compounds, the only known larger cyclodiphosphazane-based compound was tetrakis(cyclodiphosphazane) compound, $[(^t\text{BuHN})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}]_4(\mu\text{-(OCH}_2)_4\text{C})$, reported by Swamy *et al.*. The tetrakis(cyclodiphosphazane) compound was obtained from the reaction of four equivalents of **1.2** with tetrahydroxymethylmethane in THF (Scheme 6.2).¹⁹²

Up to today, among all the reported compounds, there is a ‘missing link’ of tris(cyclodiphosphazane) derivatives. This prompted us to carry out reactions to access to such frameworks to bridge the gap. For simplicity, we chose to utilize symmetrical 1,3,5-trihydroxybenzene as the core for this study.

6.2 – Syntheses of tris(cyclodiphosphazane) compounds 6.1 - 6.4

6.2.1 - Results and discussion

Scheme 6.3. Synthetic route for the formation of tris(cyclodiphosphazane) compound **6.1**.

We carried out the reaction using three equivalents of compound **1.2** with one equivalent of 1,3,5-trihydroxybenzene to generate the first tris(cyclodiphosphazane) compound (**6.1**) (Scheme 6.3). The *in situ* $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum indicated the likely formation of desired product with expected resonance signals at δ 137.3 and 105.9 ppm. Despite the numerous attempts to crystallize compound **6.1**, diffraction quality single crystals have yet to be obtained. Therefore, the reaction solvent was removed under reduced pressure and the product was extracted with hexane. The hexane filtrate was then dried to obtain white crystalline solid which was characterized by multinuclear NMR spectroscopy. The $^{31}\text{P}\{-^1\text{H}\}$ spectrum of the isolated solid exhibited two broad singlet resonances at δ 137.2 and 105.1 ppm, along with some impurities and hydrolyzed resonance signals as minor resonance peaks. While the ^1H NMR spectrum revealed expected resonance signals at δ 6.54, 2.88, 1.32 and 1.20 ppm with integration ratio of 1:1:18:9, supportive of the formation of desired compound **6.1**. Oxidation reactions were performed to potentially improve the compound stability towards air and moisture, which in turn, could aid in recrystallization of diffraction quality single crystals.

The selenide derivative, $[(^t\text{BuHN})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{Se})]_3(\mu\text{-1,3,5-O}_3\text{C}_6\text{H}_3)$ (**6.4**), was also synthesized *via* similar procedure. Crystals of compound **6.4** were obtained by recrystallization in chloroform. The $^{31}\text{P}\{-^1\text{H}\}$ NMR spectrum of **6.4** indicated two distinct sets of doublets with ^{77}Se satellites centered at δ 41.6 and 26.7 ppm with coupling constant of 13.0 Hz ($^2J_{\text{P-P}}$) and, 967.1 Hz and 884.5 Hz ($^1J_{\text{P-Se}}$) for the inner and outer phosphorus centers, respectively. The $^{31}\text{P}\{-^1\text{H}\}$ chemical shifts were comparable to that of bis(cyclodiphosphazane) compound **5.12** reported in Chapter 5, $[(^t\text{BuHN})(\text{Se})\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{Se})]_2(\mu\text{-3,5-O}_2\text{C}_6\text{H}_3(\text{CO}_2\text{Me}))$ (δ 42.1 and 26.7 ppm with coupling constant of 13.0 Hz). The ^1H and ^{13}C NMR spectroscopic analyses further supported the successful isolation of compound **6.4**.

6.2.2 - X-ray crystallographic studies of compound 6.4

Figure 6.2. ORTEP drawing of the molecular structure of compound **6.4**. The tert-butyl groups are drawn as wireframes. Thermal ellipsoids with 50 % probability at 100 K. Hydrogen atoms except H3, H6 and H9 are omitted for clarity. Selected bond lengths (Å): P1-N1 1.694(5), P1-N2 1.696(5), P2-N1 1.686(5), P2-N2 1.671(5), P1-N3 1.622(5), P3-N4 1.672(5), P3-N5 1.663(5), P4-N4 1.692(10), P4-N5 1.691(9), P4-N6 1.618(10), P5-N7 1.663(5), P5-N8 1.667(5), P6-N7 1.701(5), P6-N8 1.694(5), P6-N9 1.633(6), P2-O1 1.602(4), P3-O2 1.615(4), P5-O3 1.606(4), P1-Se1 2.0881(15), P2-Se2 2.0647(17), P3-Se3 2.0615(17), P4-Se4 2.091(7), P5-Se5 2.0683(17), P6-Se6 2.0950(16); Selected bond angles (°): P1-N1-P2 95.4(2), P1-N2-P2 95.9(2), P3-N4-P4 95.8(4), P3-N5-P4 96.2(4), P5-N7-P6 95.9(3), P5-N8-P6 96.0(3), N3-P1-N2 113.4(3), N6-P4-N5 109.2(7), N9-P6-N8 111.0(3), N1-P1-N2 83.7(2), N1-P2-N2 84.7(2), N4-P3-N5 84.6(2), N4-P4-N5 83.1(4), N7-P5-N8 85.0(2), N7-P6-N8 83.0(2), Se1-P1-N1 118.98(19), Se2-P2-O1 113.80(16), Se3-P3-O2 112.91(16), Se4-P4-N4 118.4(5), Se5-P5-O3 113.25(17), Se6-P6-N7 116.9(2).

The solid-state structure of compound **6.4** was elucidated by SC-XRD upon obtaining diffraction quality single crystals. It was found to be consistent with the proposed

structure based on the spectroscopic characterizations. All the exocyclic nitrogen and oxygen atoms of each P_2N_2 rings in compound **6.4** were found to be *cis* oriented (Fig. 6.2). The selenium atoms were *cis* with respect to the individual P_2N_2 rings. It was observed that not all the three P_2N_2 rings were on the same side of the aromatic ring which might be due to the steric congestion of the *tert*-butyl substituents present. The P_2N_2 rings attached to O1 and O3 atoms were in *cis* conformation, while the other P_2N_2 ring was *trans* to them (Fig. 6.2). The mean P=Se bond distance was calculated to be 2.078(1) Å, similar to that observed in the previously reported cyclodiphosphazane selenide, [(Se)P(μ -N^tBu)(OCH₂CH₂NMe₃)(I)]₂ and [(CyHN)(Se)P(μ -NCy)]₂ (2.065(7) and 2.091(1) Å, respectively).^{88,174} The exocyclic P-N bond distances were in the range of 1.618(10) – 1.633(10) Å, similar to that in the dimeric acyclic cyclodiphosphazane compound **5.12**, [(^tBuHN)(Se)P(μ -N^tBu)₂P]₂(μ -1,3-OC₆H₃(CO₂Me)O), synthesized earlier (1.626(3) – 1.631(3) Å). The mean endocyclic P-N and exocyclic P-O bond distances in compound **6.4** were calculated to be 1.683(6) Å and 1.608(4) Å, respectively. These bond distances were in good agreement with the typical range of such bonds found in cyclodiphosphazane-based compound, [(Se)P(μ -N^tBu)₂P(Se)(μ -1,3-OC₆H₄O)]₂ (1.685(1) and 1.601(1) Å respectively).⁵⁶ The mean Se-P-O bond angle was calculated to be 113.3(2)°, comparable to cyclodiphosphazane selenide, [(^tBuHN)(Se)P(μ -N^tBu)₂P(Se)]₂(μ -OCH₂CH₂O) (113.2(1)°).⁸² The endocyclic P-N-P and N-P-N bond angles were in the range of 95.4(2) – 96.2(4)° and 83.0(2) – 85.0(2)°, similar to that in [(^tBuHN)(Se)P(μ -N^tBu)₂P(Se)]₂(μ -OCH₂CH₂O) (95.0(1) – 96.2(1)° and 82.9(1) – 84.8(1)° respectively).⁸²

6.3 - Beyond macrocycles

It is common to work with either **1.1** or **1.2** in cyclodiphosphazane chemistry studies. However, there are no examples of cyclodiphosphazane-based compound reported from the combination of compounds **1.1**, **1.2** and multifunctional organic linkers. Moving forward, we aimed to exploit the features of **1.1** and **1.2** along with 1,3,5-trihydroxybenzene to design unique P₂N₂-based compound featuring a cyclic ring and P₂N₂ branches at terminal ends.

Figure 6.3. Examples of possible cyclodiphosphazane-based macromolecules.

Designs of two examples of macromolecular P₂N₂-based compounds were proposed as shown in Fig. 6.3 utilizing compounds **1.1**, **1.2** and 1,3,5-trihydroxybenzene.

6.3.1 - Results and discussion for synthesis of compound **6.5**

Scheme 6.5. Illustration of 1,3,5-trihydroxybenzene as reactant for formation of macromolecular compound **6.5**.

Of the two compounds, we chose to first target the synthesis of compound **6.5** which features a dimeric P₂N₂-based macrocycle as a platform linking two units of P₂N₂ rings at each end (*Scheme 6.5*). As 1,3,5-trihydroxybenzene bears three hydroxyl groups, it is of utmost concern on how to control the progress of the substitution reaction. This will depend on whether we intended to keep either (i) two or (ii) one of the three hydroxyl groups unreacted first. We proposed some synthetic routes stemming from different approaches in hope to generate the desired compound (**6.1**).

*Scheme 6.6. Proposed synthetic route to obtain acyclic disubstituted cyclodiphosphazane (**6.5'**).*

The aim of the first proposed approach was to retain two of the three hydroxyl groups. Hence, we proceeded to generate monomeric acyclic cyclodiphosphazane, [(^tBuHN)P(μ-N^tBu)₂P(OC₆H₃(OH)₂)] (**6.5'**), by adding diluted THF solution of one equivalent of **1.2** and equimolar amount of triethylamine dropwise into a diluted THF solution of equimolar amount of 1,3,5-trihydroxybenzene at -78 °C (*Scheme 6.6*). The *in situ* ³¹P-{¹H} NMR spectroscopy exhibited major resonance signals of two doublets centered at δ 129.5 (²J_{P-P} = 10.8 Hz) and 102.4 (²J_{P-P} = 6.5 Hz) ppm. We then attempted to recrystallize the product, but to no avail to date. The ³¹P-{¹H} NMR spectroscopy taken during recrystallization attempts revealed slow hydrolysis and/or decomposition of the product indicated by the appearance of resonance signals in the P(V) region (from δ 10 to -15 ppm). The ¹H NMR spectroscopy taken on crude mixture was also not conclusive due to the traces of impurities and unreacted reactants present.

Scheme 6.7. Oxidation reactions on compound **6.5'** to obtain oxidized species (**6.5'E**).

Oxidation reactions were performed with intention to improve the stability towards air and moisture. The oxidation reactions were conducted upon the completed formation of compound **6.5'**, by addition of appropriate oxidising agents to synthesize the oxidized species **6.5'E** (Scheme 6.7). The air- and moisture-stabilities of the oxidized derivatives were found to be enhanced as suggested by the ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy recorded after exposure to air and moisture for weeks. For instance, the ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy taken on **6.5'Se** revealed the same major resonance peaks, likely to correspond to the selenium oxidized product (broad singlet at δ 39.0 ppm and doublet centered at δ 26.1 ppm). Slight hydrolysis and/or decomposition took place as indicated by the presence of resonance signals at δ -0.7 ppm. However, no crystals were obtained to date.

Scheme 6.8. Alternative proposed synthetic route to obtain dimeric macrocycle (**6.5''**) with free hydroxyl groups.

With the first proposed procedure being unsuccessful, the subsequent steps planned were not carried out. We then proposed another synthetic procedure to generate dimeric macrocycle (**6.5''**) with free hydroxyl groups at both ends. One equivalent of **1.1** was reacted with equimolar amount of 1,3,5-trihydroxybenzene in presence of two

equivalents of triethylamine at -78 °C to generate dimeric macrocycle **6.5''** (Scheme 6.8). The *in situ* ^{31}P - $\{^1\text{H}\}$ NMR spectrum exhibited broad resonance signals at approximately δ 145 and 132 ppm, similar to that recorded for the reaction to obtain dimeric macrocycle **5.5**, $[\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P}(\text{OC}_6\text{H}_3(\text{CO}_2\text{Me})\text{O})_2]_2$, (singlet resonances at δ 143.1, 140.0 and 132.8 ppm with the latter being chemical shift for **5.5**). According to the ^{31}P - $\{^1\text{H}\}$ NMR spectrum, it was observed that the reaction was not exclusive, like the analogous reaction for **5.5**, resulting in a mixture of reaction products. Attempts to isolate compound **6.5''** were made, however they either led to isolation of hydrolyzed product or sticky, oily residue that still contained impurities.

Scheme 6.9. Synthesis of oxidized dimeric cyclodiphosphazane-based macrocycles, **6.5''E**.

Once again, we adapted the oxidation strategy to oxidize compound **6.5''** prior to purification steps (Scheme 6.9). For instance, the *in situ* ^{31}P - $\{^1\text{H}\}$ NMR spectroscopy of the selenium oxidation reaction showed resonance peaks indicative of formation of selenide macrocycle (*i.e.* typical range of chemical shifts corresponding to $\text{P}=\text{Se}$ moiety is δ 50 – 30 ppm).^{56,88,173,174} Both oxidation reactions were filtered and subsequently work up to attempt to obtain diffraction quality single crystals. However, all the attempts were unsuccessful thus far.

Figure 6.4. Compiled $^{31}\text{P}\{-^1\text{H}\}$ NMR spectra of compound **6.5** (top), **5.9** and **5.5** (bottom) for comparison.

Therefore, successful isolation of single crystals from the reaction mixture would be beneficial to aid identification of the structure of by SC-XRD. In addition, the purified form of the product could be characterized by multinuclear NMR spectroscopy to provide further information of the compound. After several recrystallizing attempts, diffraction quality single crystals were finally obtained from recrystallization in hexane. The ^1H NMR spectrum of dried crystals of **6.5** revealed resonance signals at δ 8.06, 6.49, 1.35, 1.24 and 1.13 ppm with the integral ratio of 1:2:18:18:9, supporting the proposed structure of **6.5** with the presence of two different P_2N_2 ring environments (two P_2N_2 rings for each environment). The formulation of **6.5** has been confirmed from the mass spectrometry, which showed a molecular ion peak at $m/z = 1207.56$ ($[\text{M}+1]^+$).

6.3.2 - X-ray crystallographic study of compound 6.5

Figure 6.5. Comparison between the structures of **6.5** (left) and **5.5** (right).

Suitable diffraction quality single crystals of **6.5** were obtained from recrystallization in hexane at room temperature. The solid-state structure of **6.5** was found to resemble closely to that of compound **5.5**, $[(P(\mu\text{-N}^t\text{Bu})_2P)(\mu\text{-3,5-OC}_6\text{H}_3(\text{CO}_2\text{Me})\text{O})]_2$, except that the ester groups were replaced with cyclodiphosphazane-based units (*i.e.* $-P(\mu\text{-N}^t\text{Bu})_2P(\text{N}^t\text{BuH})$ groups) (Fig. 6.5).

Figure 6.6. (a) ORTEP drawing of the molecular structure of compound **6.5** in wireframe (left). (b) Illustration of compound **6.5** showing the 'S-shaped'-like backbone (right). The tert-butyl groups are drawn as wireframes. Thermal ellipsoids with 50 % probability at 173 K. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å): P1-N1 1.741(4), P1-N2 1.742(4), P2-N1 1.699(4), P2-N2 1.700(3), P1-N3 1.642(4), P3-N4 1.708(4), P3-N5 1.716(4), P4-N4 1.689(4), P4-N5 1.707(4), P2-O1 1.669(3), P3-O2 1.650(3), P4-O3 1.662(3); Selected bond angles (°): P1-N1-P2 98.14(18), P1-N2-P2 98.09(18), P3-N4-P4 98.7(2), P3-N5-P4 97.7(2), N3-P1-N1 104.6(2), N3-P1-N2 105.1(2), N2-P2-O1 104.63(16), N1-P2-O1 104.77(17), N4-P3-O2 108.76(19), N4-P4-O3 99.59(17), N1-P1-N2 80.05(17), N1-P2-N2 82.44(18), N4-P3-N5 80.40(18), N4-P4-N5 81.21(18).

The single crystal X-ray structure of compound **6.5** was illustrated as Fig. 6.6. It was observed that compound **6.5** also possessed a 'S-shaped'-like structure, resembling that

in compound **5.9** (Fig. 6.6b). This ‘S-shaped’-like structure was likely attributed to the weak interaction between the exocyclic N-H protons and the π -system of the organic linkers (*i.e.* the distance between the N-H proton to the centroid of the aromatic ring: average of 2.646 Å *cf.* mean distance between the N-H $\cdots\pi$ interactions in organometallic complexes: 2.71(1) Å).¹⁹¹ The exocyclic oxygen atoms (O2 and O3) of compound **6.5** were oriented in an *exo*, *endo* manner, similar to that in the compound **5.5**, [(P(μ -N^tBu)₂P)(μ -3,5-OC₆H₃(CO₂Me)O)]₂, described previously in Chapter 5.

The mean endocyclic P(amino)-N bond distance (*i.e.* P1-N1 and P1-N2) was calculated to be 1.742(4) Å, considerably longer than that observed in the terminal P₂N₂ rings (1.689(4) – 1.714(4) Å). The P-O bond distances (1.650(3) – 1.670(4) Å) were in good agreement with that recorded for compound **5.5** and **5.9** (mean P-O bond distance: 1.661(2) and 1.686(2) Å). The endocyclic P-N-P and N-P-N bond angles (97.7(2) – 98.7(2)° and 80.1(1) – 82.4(2)°, respectively) were similar to that reported for cyclodiphosphazane bearing similar bondings, [(^tBuHN)P(μ -N^tBu)₂P]₂(μ -2-I-1,3-OC₆H₃O) (98.4(2)° and 79.7(1) – 82.9(1)° respectively).⁸³ The cavity present in **6.5** was measured to be 8.119 and 3.634 Å between the two pairs of diagonal oxygen atoms. It was slightly elongated and thinner as compared to the structural analog, [(P(μ -N^tBu)₂P)(μ -1,3-OC₆H₄O)]₂, reported by Balakrishna *et al.* (7.838 and 3.827 Å).⁵⁶ The centroids of the two bridging P₂N₂ rings in compound **6.5** was measured to be 6.962 Å, comparable to that of compound **5.5** (6.949 Å).

6.4 - Conclusion of the chapter

Tris(cyclodiphosphazane) compounds, [(^tBuHN)(E)P(μ -N^tBu)₂P(E)]₃(μ -1,3,5-C₆H₃O₃), have been synthesized and the selenide derivative (**6.4**) was successfully isolated as single crystals. These tris(cyclodiphosphazane) compounds serve to bridge the gap

between the dimeric and tetrameric acyclic derivatives. Macrocyclic arrangement, $[\text{tBuHNP}(\mu\text{-N}^t\text{Bu})_2\text{P}]_2[(\mu\text{-1,3,5-C}_6\text{H}_3\text{O}_3)(\text{P}(\mu\text{-N}^t\text{Bu})_2\text{P})]_2$ (**6.5**), was obtained and represented a new addition to the large macrocyclic cyclophosphazane family. With its unique structural features yet to be known it encourages us to further study and prepare more of such structural P_2N_2 -based compounds.

Conclusion of the thesis and Outlook

First of all, greener synthetic alternative, specifically mechanochemical ball milling, was introduced and utilized. With the use of ball milling, a variety of functionalized cyclodiphosph(III)azanes and cyclodiphosph(V)azanes were synthesized and characterized. The newly synthesized cyclodiphosph(V)azanes were tested for air- and hydrolytic-stability studies and proved to be air- and water-stable over prolonged period (*Chapter 3*). Next, a class of cyclodiphosph(III)azanes bearing P-OC(O) moiety was prepared (*Chapter 4*). Compounds **4.3** – **4.11** were the first few crystallized examples of such compounds – additions to the only reported example, [(*p*-OC(O)C₆H₄CN)P(μ -N^{*t*}Bu)]₂ (**4.1**). The *trans* macrocycle (**4.4**) was further reacted to investigate the reactivity of the P-OC(O) functionality. Two equivalents of elemental sulfur were reacted with **4.4** to generate mixed valent cyclodiphosphazane-based macrocycle **4.10**. Compound **4.10** was further reacted to produce fully oxidized derivatives (**4.10a-c**). **4.10a** and **4.10c** were new members to the family of mixed chalcogenide cyclodiphosphazane compounds. Tetrameric macrocycle **4.11** – first to be known from reacting an asymmetric organic linker and **1.1** – was prepared and recrystallized. The SC-XRD and multinuclear NMR spectroscopic analysis of **4.11** were conducted and reported. According to the SC-XRD data, two distinct resonance signals corresponding to the *tert*-butyl groups were expected on the ¹H NMR spectrum, however only one signal was observed. Change of deuterated solvent (from CDCl₃ to toluene-d₈) resulted in the split of resonance signals to two, exhibiting the chemical shifts to be solvent-dependent. On top of that, variable temperature (VT) ¹H NMR spectroscopy was further carried out and illustrated the chemical shifts were temperature-dependent. Among the reported examples of cyclodiphosphazanes, most lacked additional functional groups for further reactions to expand the applicability. Ester was chosen to be introduced into the

cyclodiphosphazane-based frameworks as it can be readily hydrolyzed or reduced to generate reactive sites. Ester-incorporated organic nucleophiles were employed to react with **1.1** or **1.2** to produce a variety of cyclodiphosphazane frameworks (**5.1** – **5.12**). The newly synthesized compounds were purified by recrystallization and characterized (*Chapter 5*). In the final chapter, trifunctional organic linker (1,3,5-trihydroxybenzene) was used to produce tris(cyclodiphosphazane) compounds (**6.1** – **6.4**) and first extended P_2N_2 -based macrocycle **6.5**. **6.1** – **6.4** were prepared to occupy the gap between bis- and tetrakis- P_2N_2 compounds (*Chapter 6*). **6.5** was the first example of such extended P_2N_2 -based compound, featuring a dimeric macrocyclic arrangement bridging two P_2N_2 rings at the terminals. Inspired by the isolation of **6.5**, work is currently ongoing to attempt to generate more of such compounds.

References

- 1 M. Lehmann, A. Schulz and A. Villinger, *Eur. J. Inorg. Chem.*, 2010, **2010**, 5501–5508.
- 2 D. C. Haagenson, L. Stahl and R. J. Staples, *Inorg. Chem.*, 2001, **40**, 4491–4493.
- 3 M. Lehmann, A. Schulz and A. Villinger, *Angew. Chem. Int. Ed.*, 2012, **51**, 8087–8091.
- 4 N. Burford, T. S. Cameron, C. L. B. Macdonald, K. N. Robertson, R. Schurko, D. Walsh, R. McDonald and R. E. Wasylshen, *Inorg. Chem.*, 2005, **44**, 8058–8064.
- 5 N. Burford, J. C. Landry, M. J. Ferguson and R. McDonald, *Inorg. Chem.*, 2005, **44**, 5897–5902.
- 6 W. Zeiss, W. Schwarz and H. Hess, *Angew. Chem. Int. Ed.*, 1977, **16**, 407–408.
- 7 C. Malavaud, T. N. M’Pondo, L. Lopez, J. Barrans and J.-P. Legros, *Can. J. Chem.*, 1984, **62**, 43–50.
- 8 M. S. Balakrishna, D. J. Eisler and T. Chivers, *Chem. Soc. Rev.*, 2007, **36**, 650–664.
- 9 A. Tarassoli, M. L. Thompson, R. C. Haltiwanger, T. G. Hill and A. D. Norman, *Inorg. Chem.*, 1988, **27**, 3382–3386.
- 10 D. Dubois, E. N. Duesler and R. T. Paine, *J. Chem. Soc., Chem. Commun.*, 1984, 488–489.
- 11 O. J. Scherer, K. Andres, C. Kriiger, Y.-H. Tsay and G. Wolmerhäuser, *Angew. Chem. Int. Ed.*, 1980, **19**, 571.
- 12 Y. X. Shi, K. Xu, J. K. Clegg, R. Ganguly, H. Hirao, T. Frišćić and F. García, *Angew. Chem. Int. Ed.*, 2016, **55**, 12736–12740.
- 13 M. M. Siddiqui, J. T. Mague and M. S. Balakrishna, *Inorg. Chem.*, 2015, **54**, 1200–1202.
- 14 R. Keat, A. N. Keith, A. Macphee, K. W. Muir and D. G. Thompson, *J. Chem.*

Soc., Chem. Commun., 1978, 1977–1978.

- 15 T. Roth, H. Wadepohl, D. S. Wright and L. H. Gade, *Chem. Eur. J.*, 2013, **19**, 13823–13837.
- 16 M. S. Balakrishna, R. Venkateswaran and J. T. Mague, *Dalton Trans.*, 2010, **39**, 11149–11162.
- 17 M. S. Balakrishna and J. T. Mague, *Organometallics*, 2007, **26**, 4677–4679.
- 18 K. V. Axenov, V. V. Kotov, M. Klinga, M. Leskelä and T. Repo, *Eur. J. Inorg. Chem.*, 2004, 695–706.
- 19 M. S. Balakrishna, *Dalton Trans.*, 2016, **45**, 12252–12282.
- 20 F. García, R. A. Kowenicki, L. Riera and D. S. Wright, *Dalton Trans.*, 2005, 2495–2496.
- 21 R. Murugavel, G. Prabusankar, A. Sharma, R. B. Sunoj and R. J. Butcher, *Inorg. Chem.*, 2009, **48**, 2048–2059.
- 22 C. Hering, A. Schulz and A. Villinger, *Chem. Sci.*, 2014, **5**, 1064.
- 23 J. M. Barendt, E. G. Bent, S. M. Young, R. C. Haltiwanger and A. D. Norman, *Inorg. Chem.*, 1991, 325–331.
- 24 E. W. Abel, D. A. Armitage and G. R. Willey, *J. Chem. Soc.*, 1965, 57–61.
- 25 N. Burford, T. S. Cameron, K. D. Conroy, B. Ellis, M. Lumsden, C. L. B. Macdonald, R. McDonald, A. D. Phillips, P. J. Ragona, R. W. Schurko, D. Walsh and R. E. Wasylshen, *J. Am. Chem. Soc.*, 2002, **124**, 14012–14013.
- 26 S. González Calera and D. S. Wright, *Dalton Trans.*, 2010, **39**, 5055–5065.
- 27 E. Niecke, M. Nieger and F. Reichert, *Angew. Chem. Int. Ed.*, 1988, **27**, 1715–1716.
- 28 A. Schulz, A. Villinger and A. Westenkirchner, *Inorg. Chem.*, 2013, **52**, 11457–11468.
- 29 A. Bashall, E. L. Doyle, F. García, G. T. Lawson, D. J. Linton, D. Moncrieff, M. McPartlin, A. D. Woods and D. S. Wright, *Chem. Eur. J.*, 2002, **8**, 5723–5731.

- 30 O. J. Scherer, R. Anselmann, R. T. Paine and S. Karthikeyan, *Inorg. Synth.*, 1980, **25**, 7–12.
- 31 O. J. Scherer and P. Klusmann, *Angew. Chem. Int. Ed.*, 1969, **8**, 752–753.
- 32 W. Zeiss and K. Barlos, *Z. Naturforsch.*, 1979, **34b**, 423–425.
- 33 D. A. Harvey, R. Keat and D. S. Rycroft, *J. Chem. Soc., Dalton Trans.*, 1983, 425–431.
- 34 M. L. Thompson, A. Tarassoli, R. C. Haltiwanger and A. D. Norman, *Inorg. Chem.*, 1987, **26**, 684–689.
- 35 K. W. Muir, *J. Chem. Soc., Dalton Trans.*, 1975, 259–262.
- 36 H.-J. Chen, R. C. Haltiwanger, T. G. Hill, M. L. Thompson, D. E. Coons and A. D. Norman, *Inorg. Chem.*, 1985, **24**, 4725–4730.
- 37 A. L. Brazeau, M. M. Hänninen, H. M. Tuononen, N. D. Jones and P. J. Ragona, *J. Am. Chem. Soc.*, 2012, **134**, 5398–5414.
- 38 F. Reiß, A. Schulz, A. Villinger and N. Weding, *Dalton Trans.*, 2010, **39**, 9962–9972.
- 39 J.-T. Ahlemann, H. W. Roesky, R. Murugavel, E. Parisini, M. Noltemeyer, H.-G. Schmidt, O. Müller, R. Herbst-Irmer, L. N. Markovskii and Y. G. Shermolovich, *Chem. Ber.*, 1997, **130**, 1113–1121.
- 40 L. Stahl, *Coord. Chem. Rev.*, 2000, **210**, 203–250.
- 41 A. Nordheider, K. Hüll, K. S. Athukorala Arachchige, A. M. Z. Slawin, J. D. Woollins, R. Thirumoorathi and T. Chivers, *Dalton Trans.*, 2015, **44**, 5338–5346.
- 42 H.-C. Niu, A. J. Plajer, R. Garcia-Rodriguez, S. Singh and D. S. Wright, *Chem. Eur. J.*, 2018, **24**, 3073–3082.
- 43 M. M. Siddiqui, J. T. Mague and M. S. Balakrishna, *Inorg. Chem.*, 2015, **54**, 6063–6065.
- 44 P. Chandrasekaran, J. T. Mague and M. S. Balakrishna, *Dalton Trans.*, 2007, 2957–2962.

- 45 P. Chandrasekaran, J. T. Mague and M. S. Balakrishna, *Inorg. Chem.*, 2006, **45**, 6678.
- 46 M. E. Otang, G. R. Lief and L. Stahl, *J. Organomet. Chem.*, 2016, **820**, 98–110.
- 47 M. Rastätter, R. B. Mutterle, P. W. Roesky and S. K. H. Thiele, *Chem. Eur. J.*, 2009, **15**, 474–481.
- 48 K. Albahily, Z. Ahmed, S. Gambarotta, E. Koc and R. Duchateau, *Organometallics*, 2011, **30**, 6022–6027.
- 49 K. V. Axenov, M. Leskelä and T. Repo, *J. Catal.*, 2006, **238**, 196–205.
- 50 D. Suresh, M. S. Balakrishna, K. Rathinasamy, D. Panda and S. M. Mobin, *Dalton Trans.*, 2008, **1**, 2812–2814.
- 51 M. S. Balakrishna, S. Devarajan, A. Rai, J. T. Mague and D. Panda, *Inorg. Chem.*, 2010, **49**, 8790–8801.
- 52 A. Rashid, G. S. Ananthnag, S. Naik, J. T. Mague, D. Panda and M. S. Balakrishna, *Dalton Trans.*, 2014, 11339–11351.
- 53 G. R. Lief, D. F. Moser, L. Stahl and R. J. Staples, *J. Organomet. Chem.*, 2004, **689**, 1110–1121.
- 54 D. Suresh, M. S. Balakrishna and J. T. Mague, *Tetrahedron Lett.*, 2007, **48**, 2283–2285.
- 55 G. David, E. Niecke, M. Nieger, V. Von Der Gönna and W. W. Schoeller, *Chem. Ber.*, 1993, **126**, 1513–1517.
- 56 G. S. Ananthnag, S. Kuntavalli, J. T. Mague and M. S. Balakrishna, *Inorg. Chem.*, 2012, **51**, 5919–5930.
- 57 A. D. Woods and M. McPartlin, *Dalton Trans.*, 2004, 90–93.
- 58 R. Keat and D. G. Thompson, *J. Chem. Soc., Dalton Trans.*, 1980, 321–326.
- 59 M. Vijjulatha, K. C. Kumara Swamy, J. J. Vittal and L. L. Koh, *Polyhedron*, 1999, **18**, 2249–2254.
- 60 Y. Sim, D. Tan, R. Ganguly, Y. Li and F. García, *Chem. Commun.*, 2018, **54**, 6800–6803.

- 61 I. Schranz, L. Stahl and R. J. Staples, *Inorg. Chem.*, 1998, **37**, 1493–1498.
- 62 R. R. Holmes and J. A. Forstner, *Inorg. Chem.*, 1963, **2**, 380–384.
- 63 J. K. Brask, T. Chivers, M. L. Krahn and M. Parvez, *Inorg. Chem.*, 1999, **38**, 290–295.
- 64 D. Dou, E. N. Duesler and R. T. Paine, *Inorg. Chem.*, 1999, **38**, 788–793.
- 65 A. D. Bond, E. L. Doyle, F. García, R. A. Kowenicki, M. Mcpartlin, L. Riera and D. S. Wright, *Chem. Commun.*, 2003, 2990–2991.
- 66 S. González Calera, D. J. Eisler, J. M. Goodman, M. McPartlin, S. Singh and D. S. Wright, *Dalton Trans.*, 2009, **2**, 1293.
- 67 A. Bashall, E. L. Doyle, C. Tubb, S. J. Kidd, M. McPartlin, A. D. Woods and D. S. Wright, *Chem. Commun.*, 2001, **0**, 2542–2543.
- 68 A. Bashall, A. D. Bond, E. L. Doyle, F. García, S. Kidd, G. T. Lawson, M. C. Parry, M. McPartlin, A. D. Woods and D. S. Wright, *Chem. Eur. J.*, 2002, **8**, 3377–3385.
- 69 F. García, J. M. Goodman, R. A. Kowenicki, I. Kuzu, M. McPartlin, M. A. Silva, L. Riera, A. D. Woods and D. S. Wright, *Chem. Eur. J.*, 2004, **10**, 6066–6072.
- 70 F. García, R. A. Kowenicki, I. Kuzu, M. McPartlin, L. Riera and D. S. Wright, *Inorg. Chem. Commun.*, 2005, **8**, 1060–1062.
- 71 A. Nordheider, T. Chivers, R. Thirumoorthi, I. Vargas-Baca and J. D. Woollins, *Chem. Commun.*, 2012, **48**, 6346.
- 72 A. J. Plajer, R. García-Rodríguez, C. G. M. Benson, P. D. Matthews, A. D. Bond, S. Singh, L. H. Gade and D. S. Wright, *Angew. Chem. Int. Ed.*, 2017, 9087–9090.
- 73 A. J. Plajer, H.-C. Niu, F. J. Rizzuto and D. S. Wright, *Dalton Trans.*, 2018, **47**, 6675–6678.
- 74 D. Bawari, B. Prashanth, S. Ravi, K. R. Shamasundar, S. Singh and D. S. Wright, *Chem. Eur. J.*, 2016, **22**, 12027–12033.

- 75 S. González Calera, D. J. Eisler, J. V. Morey, M. McPartlin, S. Singh and D. S. Wright, *Angew. Chem. Int. Ed.*, 2008, **47**, 1111–1114.
- 76 S. S. Kumaravel, S. S. Krishnamurthy, T. S. Cameron and A. Linden, *Inorg. Chem.*, 1988, **27**, 4546–4550.
- 77 M. Vijjulatha, S. Kumaraswamy, K. C. K. Swamy and U. Engelhardt, *Polyhedron*, 1999, **18**, 2557–2562.
- 78 F. García, R. A. Kowenicki, I. Kuzu, L. Riera, M. McPartlin and D. S. Wright, *Dalton Trans.*, 2004, **7**, 2904–2909.
- 79 F. García, J. M. Goodman, R. A. Kowenicki, M. McPartlin, L. Riera, M. A. Silva, A. Wirsing and D. S. Wright, *Dalton Trans.*, 2005, 1764–1773.
- 80 M. A. Beswick, B. R. Elvidge, N. Feeder, S. J. Kidd and D. S. Wright, *Chem. Commun.*, 2001, **663**, 379–380.
- 81 E. L. Doyle, F. García, S. M. Humphrey, R. A. Kowenicki, L. Riera, A. D. Woods and D. S. Wright, *Dalton Trans.*, 2004, 807–812.
- 82 M. S. Balakrishna, R. Venkateswaran and J. T. Mague, *Inorg. Chem.*, 2009, **48**, 1398–1406.
- 83 G. S. Ananthnag, J. T. Mague and M. S. Balakrishna, *Dalton Trans.*, 2015, **44**, 3785–3793.
- 84 W. T. K. Chan, D. Eisler, F. García, S. González Calera, M. McPartlin, J. V. Morey, R. E. Mulvey, S. Singh, A. Steiner and D. S. Wright, *Chem. Commun.*, 2008, 2251–2253.
- 85 C. G. M. Benson, A. J. Plajer, R. García-Rodríguez, A. D. Bond, S. Singh, L. H. Gade and D. S. Wright, *Chem. Commun.*, 2016, **52**, 9683–9686.
- 86 A. Nordheider, T. Chivers, R. Thirumoorthi, K. S. Athukorala Arachchige, A. M. Z. Slawin, J. D. Woollins and I. Vargas-Baca, *Dalton Trans.*, 2013, **42**, 3291–3294.
- 87 G. G. Briand, T. Chivers and G. Schatte, *Inorg. Chem.*, 2002, **41**, 1958–1965.
- 88 P. Chandrasekaran, J. T. Mague and M. S. Balakrishna, *Eur. J. Inorg. Chem.*, 2011, 2264–2272.

- 89 D. Tan, Z. X. Ng, Y. Sim, R. Ganguly and F. García, *CrystEngComm*, , DOI:10.1039/C8CE00395E.
- 90 L. Manojlović-Muir and K. W. Muir, *J. Chem. Soc., Dalton Trans.*, 1974, 2395–2398.
- 91 Y. X. Shi, R. Z. Liang, K. A. Martin, N. Weston, S. González Calera, R. Ganguly, Y. Li, Y. Lu, A. J. M. Ribeiro, M. J. Ramos, P. A. Fernandes and F. García, *Inorg. Chem.*, 2015, **54**, 6423–6432.
- 92 G. R. Lief, C. J. Carrow, L. Stahl and R. J. Staples, *Organometallics*, 2001, **20**, 1629–1635.
- 93 T. G. Hill, R. C. Haltiwanger, M. L. Thompson, S. A. Katz and A. D. Norman, *Inorg. Chem.*, 1994, **33**, 1770–1777.
- 94 T. Chivers, M. Krahn and M. Parvez, *Chem. Commun.*, 2000, **14**, 463–464.
- 95 Y. X. Shi, R. Z. Liang, K. A. Martin, D. G. Star, J. Díaz, X. Y. Li, R. Ganguly and F. García, *Chem. Commun.*, 2015, **51**, 16468–16471.
- 96 Y. X. Shi, K. A. Martin, R. Z. Liang, D. G. Star, Y. Li, R. Ganguly, Y. Sim, D. Tan, J. Díaz and F. García, *Inorg. Chem.*, , DOI:10.1021/acs.inorgchem.8b01596.
- 97 V. S. Kashid, J. T. Mague and M. S. Balakrishna, *J. Chem. Sci.*, 2017, **129**, 1531–1537.
- 98 P. Kommana and K. C. Kumara Swamy, *Inorg. Chem.*, 2000, **39**, 4384–4385.
- 99 K. V. Axenov, M. Klinga, M. Leskelä and T. Repo, *Organometallics*, 2005, **24**, 1336–1343.
- 100 G. S. Ananthnag, J. T. Mague and M. S. Balakrishna, *J. Chem. Sci.*, 2015, **127**, 979–986.
- 101 M. S. Balakrishna, *J. Organomet. Chem.*, 2010, **695**, 925–936.
- 102 D. F. Moser, C. J. Carrow, L. Stahl and R. J. Staples, *J. Chem. Soc., Dalton Trans.*, 2001, 1246–1252.
- 103 L. Grocholl, L. Stahl and R. J. Staples, *Chem. Commun.*, 1997, **2**, 1465–1466.

- 104 G. Bai, H. W. Roesky, M. Noltemeyer and H.-G. Schmidt, *Organometallics*, 2002, **21**, 2789–2792.
- 105 K. V. Axenov, I. Kilpeläinen, M. Klinga, M. Leskelä and T. Repo, *Organometallics*, 2006, **25**, 463–471.
- 106 L. Grocholl, I. Schranz, L. Stahl and R. J. Staples, *Inorg. Chem.*, 1998, **37**, 2496–2499.
- 107 I. Schranz and L. Stahl, *Inorganica Chim. Acta*, 2010, **363**, 975–980.
- 108 I. Schranz, L. Grocholl, C. J. Carrow, L. Stahl and R. J. Staples, *J. Organomet. Chem.*, 2008, **693**, 1081–1095.
- 109 I. Schranz, L. P. Grocholl, L. Stahl, R. J. Staples and A. Johnson, *Inorg. Chem.*, 2000, **39**, 3037–3041.
- 110 D. F. Moser, I. Schranz, M. C. Gerrety and R. J. Staples, *J. Chem. Soc., Dalton Trans.*, 1999, 751–757.
- 111 A. Tarassoli, R. C. Haltiwanger and A. D. Norman, *Inorg. Chem.*, 1982, **21**, 2684–2690.
- 112 I. Silaghi-Dumitrescu and I. Haiduc, *Phosphorus. Sulfur. Silicon Relat. Elem.*, 1994, **91**, 21–36.
- 113 E. Hobbs, D. E. C. Corbridge and B. Raistrick, *Acta Crystallogr.*, 1953, **6**, 621.
- 114 L. Pauling, *The Nature of the Chemical Bond and the Structure of Molecules and Crystals, Chapter 3: The Partial Ionic Character of Covalent Bonds and the Relative Electronegativity of Atoms*, Cornell University Press, 3rd edn., 1960.
- 115 W. W. Schoeller and C. Lerch, *Inorg. Chem.*, 1986, **25**, 576–580.
- 116 S. Wolfe, *Acc. Chem. Res.*, 1972, **5**, 102–111.
- 117 K. Miqueu, J.-M. Sotiropoulos, G. Pfister-Guillouzo and V. D. Romanenko, *New J. Chem.*, 2001, **25**, 930–938.
- 118 A. E. Reed and P. V. R. Schleyer, *Inorg. Chem.*, 1988, **27**, 3969–3987.
- 119 APEX2, Bruker AXS Inc., Madison, WI, 2004.

- 120 G. M. Sheldrick, *SHELXL-97: Program for the Refinement of Crystal Structures*, University of Göttingen, Germany, 1997.
- 121 G. M. Sheldrick, *CELL_NOW*, University of Göttingen, Germany, 2008.
- 122 G. M. Sheldrick, *TWINABS*, University of Göttingen, Germany, 2008.
- 123 W. L. F. Armarego and C. L. L. Chai, *Purification of Organic Chemicals*, Elsevier Inc., 6th Ed., 2009.
- 124 R. Jefferson, J. F. Nixon, T. M. Painter, R. Keat and L. Stobbs, *J. Chem. Soc., Dalton Trans.*, 1973, 1414–1419.
- 125 C. G. M. Benson, V. Vasilenko, R. García-Rodríguez, A. D. Bond, S. González Calera, L. H. Gade and D. S. Wright, *Dalton Trans.*, 2015, **44**, 14242–14247.
- 126 R. Sevilla, R. J. Less, R. García-Rodríguez, A. D. Bond and D. S. Wright, *Dalton Trans.*, 2016, **45**, 1868–1871.
- 127 R. A. Sheldon, *Green Chem.*, 2005, **7**, 267–278.
- 128 A. Stolle, T. Szuppa, S. E. S. Leonhardt and B. Ondruschka, *Chem. Soc. Rev.*, 2011, **40**, 2317–2329.
- 129 T. Friščić, *Chem. Soc. Rev.*, 2012, **41**, 3493–3510.
- 130 L. Chen, B. E. Lemma, J. S. Rich and J. Mack, *Green Chem.*, 2014, **16**, 1101–1103.
- 131 J. L. Do and T. Friščić, *ACS Cent. Sci.*, 2017, **3**, 13–19.
- 132 G.-W. Wang, *Chem. Soc. Rev.*, 2013, **42**, 7668–7700.
- 133 S. L. James, C. J. Adams, C. Bolm, D. Braga, P. Collier, T. Friščić, F. Grepioni, K. D. M. Harris, G. Hyett, W. Jones, A. Krebs, J. Mack, L. Maini, A. G. Orpen, I. P. Parkin, W. C. Shearouse, J. W. Steed and D. C. Waddell, *Chem. Soc. Rev.*, 2012, **41**, 413–447.
- 134 S.-E. Zhu, F. Li and G.-W. Wang, *Chem. Soc. Rev.*, 2013, **42**, 7535.
- 135 A. Beillard, X. Bantreil, T.-X. Métro, J. Martinez and F. Lamaty, *Dalton Trans.*, 2016, **45**, 17859–17866.

- 136 E. Boldyreva, *Chem. Soc. Rev.*, 2013, **42**, 7719.
- 137 C. Xu, S. De, A. M. Balu, M. Ojeda and R. Luque, *Chem. Commun.*, 2015, **51**, 6698–6713.
- 138 K. S. Suslick, *Faraday Discuss.*, 2014, **170**, 411–422.
- 139 D. Tan and T. Friščić, *Chem. Commun.*, 2017, **53**, 901–904.
- 140 D. Tan and T. Friščić, *Eur. J. Org. Chem.*, 2018, 18–33.
- 141 D. E. Crawford, C. K. G. Miskimmin, A. B. Albadarin, G. Walker and S. L. James, *Green Chem.*, 2017, **19**, 1507–1518.
- 142 J. L. Howard, Y. Sagatov, L. Repousseau, C. Schotten and D. L. Browne, *Green Chem.*, 2017, **19**, 2798–2802.
- 143 P. K. Sahoo, C. Giri, T. S. Haldar, R. Puttreddy, K. Rissanen and P. Mal, *European J. Org. Chem.*, 2016, **2016**, 1283–1291.
- 144 J. G. Hernández and C. Bolm, *Chem. Commun.*, 2015, **51**, 12582–12584.
- 145 M. Juribašić, K. Užarević, D. Gracin and M. Ćurić, *Chem. Commun.*, 2014, **50**, 10287–10290.
- 146 V. D. Makhaev, A. P. Borisov and L. A. Petrova, *J. Organomet. Chem.*, 1999, **590**, 222–226.
- 147 J. D. Egbert, A. M. Z. Slawin and S. P. Nolan, *Organometallics*, 2013, **32**, 2271–2274.
- 148 N. R. Rightmire and T. P. Hanusa, *Dalton Trans.*, 2016, **45**, 2352–2362.
- 149 J. G. Hernández, I. S. Butler and T. Friščić, *Chem. Sci.*, 2014, **5**, 3576–3582.
- 150 K. J. Reimer and A. Shaver, *Inorg. Synth.*, 1990, **28**, 154–159.
- 151 S. P. Schmidt, W. C. Trogler and F. Basolo, *Inorg. Synth.*, 1990, **28**, 160–165.
- 152 A. Beillard, T.-X. Métro, X. Bantreil, J. Martinez and F. Lamaty, *Chem. Sci.*, 2017, **8**, 1086–1089.
- 153 D. W. Peters and R. G. Blair, *Faraday Discuss.*, 2014, **170**, 83–91.
- 154 N. C. Boyde, N. R. Rightmire, T. P. Hanusa and W. W. Brennessel, *Inorganics*,

- 2017, **5**, 36–46.
- 155 N. R. Rightmire, T. P. Hanusa and A. L. Rheingold, *Organometallics*, 2014, **33**, 5952–5955.
 - 156 N. R. Rightmire, D. L. Bruns, T. P. Hanusa and W. W. Brennessel, *Organometallics*, 2016, **35**, 1698–1706.
 - 157 T. Friščić, A. V. Trask, W. Jones and W. D. S. Motherwell, *Angew. Chemie - Int. Ed.*, 2006, **45**, 7546–7550.
 - 158 M. Glavinović, M. Krause, L. Yang, J. A. McLeod, L. Liu, K. M. Baines, T. Friščić and J.-P. Lumb, *Sci. Adv.*, 2017, **3**, e1700149.
 - 159 J. Wang, R. Ganguly, L. Yongxin, J. Díaz, H. Sen Soo and F. García, *Dalton Trans.*, 2016, **45**, 7941–7946.
 - 160 A. L. Gottumukkala, J. F. Teichert, D. Heijnen, N. Eisink, S. Van Dijk, C. Ferrer, A. Van Den Hoogenband and A. J. Minnaard, *J. Org. Chem.*, 2011, **76**, 3498–3501.
 - 161 F. Ragaini, S. Cenini, S. Tollari, G. Tummolillo and R. Beltrami, *Organometallics*, 1999, **18**, 928–942.
 - 162 D. Tan, C. Mottillo, A. D. Katsenis, V. Štrukil and T. Friščić, *Angew. Chem. Int. Ed.*, 2014, **53**, 9321–9324.
 - 163 V. Štrukil, D. Gracin, O. V. Magdysyuk, R. E. Dinnebier and T. Friščić, *Angew. Chem. Int. Ed.*, 2015, **54**, 8440–8443.
 - 164 D. F. Moser, L. Grocholl, L. Stahl and R. J. Staples, *Dalton Trans.*, 2003, 1402–1410.
 - 165 M. Kuprat, M. Lehmann, A. Schulz and A. Villinger, *Inorg. Chem.*, 2011, **50**, 5784–5792.
 - 166 Y. Sim, Y. X. Shi, R. Ganguly, Y. Li and F. García, *Chem. Eur. J.*, 2017, **23**, 11279–11285.
 - 167 C. Fonseca Guerra, F. M. Bickelhaupt, S. Sana and F. Wang, *J. Phys. Chem. A*, 2006, **110**, 4012–4020.

- 168 T. Roth, V. Vasilenko, H. Wadepohl, D. S. Wright and L. H. Gade, *Inorg. Chem.*, 2015, **54**, 7636–7644.
- 169 C. H. Wong and S. C. Zimmerman, *Chem. Commun.*, 2013, **49**, 1679–1695.
- 170 P. K. Sahoo, A. Bose and P. Mal, *European J. Org. Chem.*, 2015, **2015**, 6994–6998.
- 171 L. A. Polindara-García and E. Juaristi, *European J. Org. Chem.*, 2016, **2016**, 1095–1102.
- 172 T. Chivers, M. Krahn and G. Schatte, *Inorg. Chem.*, 2002, **41**, 4348–4354.
- 173 G. S. Ananthnag, J. T. Mague and M. S. Balakrishna, *J. Organomet. Chem.*, 2015, **779**, 45–54.
- 174 M. S. Balakrishna, D. Suresh, G. S. Ananthnag and J. T. Mague, *Dalton Trans.*, 2014, **43**, 8835–48.
- 175 M. S. Balakrishna, D. Suresh and J. T. Mague, *Eur. J. Inorg. Chem.*, 2010, **2010**, 4201–4210.
- 176 H. Klare, S. Hanft, J. M. Neudörfl, N. E. Schlörer, A. Griesbeck and B. Goldfuss, *Chem. Eur. J.*, 2014, **20**, 11847–11855.
- 177 T. Chivers, M. Krahn, M. Parvez and G. Schatte, *Inorg. Chem.*, 2001, **40**, 2547–2553.
- 178 W. A. Kamil, M. R. Bond, R. D. Willett and J. M. Shreeve, *Inorg. Chem.*, 1987, **26**, 2829–2833.
- 179 A. Brückner, A. Hinz, J. B. Priebe, A. Schulz and A. Villinger, *Angew. Chem. Int. Ed.*, 2015, **54**, 7426–7430.
- 180 F. Dodds, F. García, R. A. Kowenicki, S. P. Parsons, M. McPartlin and D. S. Wright, *Dalton Trans.*, 2006, **2**, 4235–4243.
- 181 F. Dodds, F. García, R. A. Kowenicki, M. McPartlin, L. Riera, A. Steiner and D. S. Wright, *Chem. Commun.*, 2005, **1**, 5041–5043.
- 182 J. Kim and D. O. Jang, *Synth. Commun.*, 2001, **31**, 395–399.
- 183 F. Di Gregorio and W. Marconi, *J. Org. Chem.*, 1981, **46**, 4569–4570.

- 184 D. S. Wright, *Host-Guest Chemistry - p-Block Systems*, Elsevier Ltd., 2013, vol. 1.
- 185 A. S. Ionkin, S. N. Ignat'eva, I. A. Litvinov, V. A. Naumov and B. A. Arbuzov, *Heteroat. Chem.*, 1992, **3**, 459–461.
- 186 K. C. Kumara Swamy, G. Gangadhararao, V. Srinivas, N. N. Bhuvan Kumar, E. Balaraman and M. Chakravarty, *Inorganica Chim. Acta*, 2011, **372**, 374–382.
- 187 M. Chakravarty, R. R. Suresh and K. C. K. Swamy, *Inorg. Chem.*, 2007, **46**, 9819–9826.
- 188 V. S. Reddy, S. S. Krishnamurthy and M. Nethaji, *J. Chem. Soc., Dalton Trans.*, 1994, **2**, 2661–2667.
- 189 M. Chakravarty, P. Kommana and K. C. K. Swamy, *Chem. Commun.*, 2005, **28**, 5396.
- 190 Z. Zák and G. Ohms, *Z. Kristallogr.*, 1995, **210**, 301–301.
- 191 D. Braga, F. Grepioni and E. Tedesco, *Organometallics*, 1998, **17**, 2669–2672.
- 192 P. Kommana, J. J. Vittal and K. C. Kumara Swamy, *Polyhedron*, 2003, **22**, 843–847.

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D. Tan, Z. X. Ng, Y. Sim, R. Ganguly and F. García*, *CrystEngComm*, 2018, **20**, 5998–6004.

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Y X. Shi, K. Martin, R. Z. Liang, D. Starr, Y. Li, R. Ganguly, Y. Sim, D. Tan and F. García*, *Inorg. Chem.*, 2018, **57**, 17, 10993–11004.