Exploring Trianglamine Derivatives and Trianglamine Coordination Complexes as Porous Organic Materials

Thesis by
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ABSTRACT

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Magdalene Eziashi

Trianglamines are triangular chiral macrocycles that were first synthesized by Gawronski’s group in Poland in the year 2000. Despite their unique properties; triangular pore shape, chirality, symmetric structure and tunable pore size, they are still a poorly researched class of macrocycles today. Trianglamines have yet a role to play as porous organic molecules for separation processes, as macrocyclic precursors to build increasingly complex supramolecular assemblies and as building blocks for caged porous organic structures. The aim of the Thesis work is to explore trianglamine, its derivatives, and assemblies as viable porous organic molecules for potential gas capture and separation.
ACKNOWLEDGEMENTS

Jeremiah 9:23-24a

23 *This is what the Lord says:
The wise person should not boast in his wisdom;
the strong should not boast in his strength;
the wealthy should not boast in his wealth.

24 But the one who boasts should boast in this:
that he understands and knows me... ’

Firstly, I give all praise to the One who is my daily sustenance and ever-present help.

I am always grateful to my family for their constant love and support – my degree would not have been easy without them. Many thanks to my academic advisor Prof. Niveen Khashab, and laboratory supervisor, Dr. Carine Maaliki for both their support in my academic and scientific endeavours. Thanks to Dr. Mouchaham for many suggestions and technical support. Special thanks are given to Dr. Maaliki who has been a patient teacher and constant source of guidance and support throughout this project.
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<tr>
<td>MOF</td>
<td>Metal Organic Framework</td>
</tr>
<tr>
<td>COF</td>
<td>Covalent Organic Framework</td>
</tr>
<tr>
<td>HOF</td>
<td>Hydrogen-bonded Organic Framework</td>
</tr>
<tr>
<td>PCP</td>
<td>Porous Coordination Polymers</td>
</tr>
<tr>
<td>POM</td>
<td>Porous Organic Molecules</td>
</tr>
<tr>
<td>BET</td>
<td>Brunauer-Emmett-Teller</td>
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<td>DCM</td>
<td>Dichloromethane</td>
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INTRODUCTION

Porous materials have had huge societal contributions over the past millennia and are present in materials we use in everyday life and to materials manufactured for industrial applications. From charcoal to earthen clays and terracotta, porous materials have always been of value in society. Over the past couple of decades, porous materials have become increasingly important for an innumerable range of industrial applications which include separation processes, chemical purifications and catalysis methods. For a material to be porous, it must have voids or pores through which liquids or gases may pass, these voids should remain permanent and not collapse when desolvated or degassed i.e. shape-persistent voids. One of the most industrially and societally relevant porous materials are zeolites. Since the 1970's zeolites alone have revolutionized many industrial and domestic processes such as water filtration, water softening, gas and chemical separation.\textsuperscript{2-3} Despite their advantages and their wide range of applications, zeolites generally lack chemical tolerance to acid and bases, stability at atmospheric moisture levels and chemical functionalities for chemical group modification.\textsuperscript{4-5}

In the 1990's metals complexed to organic subunits were realized, such as metal organic frameworks (MOFs), porous coordination polymers (PCP's) and covalent organic frameworks (COFs).\textsuperscript{6-8} These materials are all linked by their design, which is the formation of strong coordination and/or covalent bonds between the organic building blocks.\textsuperscript{9} These extended organic frameworks have advantages over zeolites due to their regular and ordered porous structures and their ability to be designed via a “bottom-up” approach.\textsuperscript{7} From the class of porous organic materials comes still a unique subset; porous organic molecules (POM’s). POM’s can be defined as molecules that pack in the solid state and produce pores. These pores can be formed as a result of directional
non-covalent bonding such as hydrogen bonding, or because of the inefficient packing of the molecules due to their rigid and “awkward” structures. In most of these cases, the porosity achieved will be extrinsic, i.e., porosity formed between the molecules rather than within the molecule itself. Little attention has been paid to POM’s despite their advantages such as solution processibility and easy functionalization. Their disadvantages arise from their efficient packing, hence reduced void space, and after desolvation, there is usually a collapse in their supramolecular assembly and hence no permanent porosity.

Two significant design strategies can be considered when building molecular organic porous materials that can compete with existing organic porous materials. Firstly, there is a need to design POM’s with inherent intrinsic porosity within their structure, as they tend to have superior Brunauer-Emmett-Teller (BET) surface areas in comparison to materials which solely form extrinsic pores like most MOF’s, COF’s and organic cages. Secondly, solution processibility offers various desirable advantages such as possible purification procedures via recrystallization and chromatography, hence competing with existing porous organic materials and porous extended frameworks. There is a need to design porous materials with intrinsic porosity (shape-persistent voids) as they tend to have superior BET surface areas in comparison to materials which from extrinsic pores. For this reason, trianglamines appear useful due to their intrinsic triangle-shaped pores, and with successful manipulation, they can be suitable precursors for supramolecular assembly with possible areas of application in gas and chemical storage and separation.
1. Trianglamines

Since the 90s, studies on macrocycles, such as trianglamines, have found great significance. Trianglimines are synthesized via a [3+3] thermodynamically controlled imine condensation reaction between equimolar amounts of both dialdehydes and diamines. The trianglamine is then achieved by the reduction of the trianglimine. The subsequent reduction of trianglimines have received more attention due to their greater chemical stability. While the trianglimines have limited applications due to the instability of the imine bond, their reduced forms have already been used as chiral agents, ligands, organocatalysts and most recently for their photochromic properties.

Scheme 1. General procedure for trianglamine synthesis.

Gawronski first reported in the year 2000, the synthetic strategy for the synthesis of these trianglamines via the [3+3] cyclocondensation. The condensation of chiral amines, such as (1R,2R)-1, 2-diaminocyclohexane, with aromatic dialdehydes, such as terephthalaldehyde and isophthalaldehyde, were reported. The two C-N bonds in the diamine are projected at a 60° angle from the centre of the cyclohexane ring and hence
macrocycle formation is confirmed to proceed through a \([3 + 3]\) diamine-dialdehyde addition.\(^1\) The formation of the imine was followed by \(^1\)H NMR in chloroform. The aldehyde signal at 10.2 ppm rapidly evolves to the imine signal at 8.15 ppm suggesting the occurrence of the imination reaction. In 2003, Gawronski used hydroxydialdehydes as the reactant to form the trianglamine, and proposed the term ‘calixsalen’,\(^{25}\) due to the formation of vase-like macrocycles, similar to the well-established calixarenes.\(^{26}\) It is the hydroxyl group on the dialdehyde that stabilizes the structure of the cyclic trianglimine product due to the strong electronic donation effect of the OH−−N bond. More recently, there has been a significant number of studies carried out on calixsalens and their potential application.\(^{27-30}\)

During the same period as Gawronski’s work, Kuhnert’s research group also carried out various studies to create a library of trianglamine compounds by varying the alkyl,\(^{32}\) aromatic\(^{33}\) and oxygenated aromatic\(^{34}\) dicarboxaldehydes. Due to their unique triangular shape, this group first proposed to name the macrocycle as ‘trianglimines’ and ‘trianglamines’. Last year, Olson noted that the nature of the substituent of the aromatic moiety directly relates to both the structure and properties of the products. He was able to synthesize a large panel of dialdehyde linkers which therefore could alter

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**Figure 1.** Nomenclature of trianglamines.\(^{31}\)
the size of the intrinsic cavity formed,\textsuperscript{32,35-36} hence opening the door to a large panel of macrocycles and thus a larger library of molecules for the exploration of new properties and applications.

1.1 Trianglamine Stereochemistry

There are different stereochemical classes that a trianglamine can fit into, depending on the stereochemistry of the starting diamino e.g. 1,2-diaminocyclohexane. The stereochemistry of the diaminocyclohexane has a part to play on the final geometry/conformation and dictates the chirality of the final trianglamine compound.\textsuperscript{37-41}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The various isomers and enantiomers of 1,2-diaminocyclohexane.}
\end{figure}

By using diaminocyclohexanes with no chiral centres, such as the cis-1,2-diaminocyclohexane, we can forfeit the chirality of the trianglamine or synthesize enantiomerically pure, chiral trianglamines by using a single enantiomeric form of the diaminocyclohexane such as (1S,2S)-(+) diaminocyclohexane. The synthesis of enantiomerically pure trianglamine derivatives have gained a lot of attention because uniform chirality in macrocycles offers them the ability to be used as potential receptors for chiral recognition.\textsuperscript{40-41}

1.2 Trianglamine Functionalization
In early 2006, Gawroski’s team reported the first successful post-synthesis functionalization of trianglamine,\textsuperscript{31} and was followed closely by Kunhert’s group who released a paper on a similar achievement later that year.\textsuperscript{37} Gawronksi was able to carry out the alkylation on the NH moiety of the trianglamine by reacting it with the corresponding alkyl bromide in the presence of potassium carbonate, achieving yields of approximately 40-70%.

Figure 3. Reported N-functionalized trianglamine derivatives.\textsuperscript{31}

Gawronski’s team report that a range of different conformations for trianglamines, are observed in the solid state, depending on the solvent system and counterions present. They attribute this phenomenon the conformational flexibility of trianglamine. They also noted the tendency of trianglamine to minimize the cavity size in the absence of guest molecules, but rather when functionalized, molecules 1-11 (Figure 3), had a smaller ability to include guest molecules. These deductions were made when studying the inclusion of benzene-1, 3, 5-tricarboxylic acid against its 1, 2, 3- and 1, 2, 4-isomers.\textsuperscript{31}

Similarly, Kunhert’s group reported both N-alkylation and N-acylation. They achieved N-alkylated trianglamines by using bromoacetate esters, giving high yields 80-97%, and also by alkyl dibromides, giving much poorer yields of approximately 20%. N-
acylation was successfully carried out using acyl chloride derivatives, resulting in trianglamines in high yields between 80-97%. The suggested application for these N-acylated and N-alkylated derivatives are as chiral molecular synthetic receptors due to the ability to synthesize these enantiomerically pure chiral trianglamine derivatives.\textsuperscript{37}

![Figure 4. Reported N-acylated trianglamine derivatives.\textsuperscript{37}](image)

Another synthetic approach has also been taken to achieve functionalized trianglamine derivatives via a pre-functionalization approach i.e. by reacting (\(R,R\))-N,N-diisopropyl-1,2-diaminocyclohexane with benzylic dibromide derivatives to obtain chiral macrocycles. Unlike the conventional [3+3] imination reaction, this trianglamine synthesis occurs through a nucleophilic substitution reaction, and in the case of the 1,4-benzyl bromide, two products are formed (Figure 5). According to Mass Spectrometry (MS), they could detect the presence of both C\(_2\) symmetric macrocycle, with a yield of >95\%, and the C3 symmetric trianglamine with <5\% yield, that could not even be isolated. From this paper, it appears this “bottom-up” synthesis approach may not be most efficient for functionalized trianglamine synthesis. In this paper, they did not report any applications tested for the macrocycles, but the importance of chiral macrocycles as receptors for peptide and amino acid recognition was mentioned.\textsuperscript{38}
In the aforementioned papers of this section, nothing was reported regarding the gas adsorption properties of the supramolecular assemblies of these trianglamine derivatives.

### 1.3 Trianglamine-Metal Coordinations

Chiral macrocycles with multinuclear sites are of great importance to synthetically mimic the activity and behaviour of biologically important enzymes. Based on the ease at which trianglimines and trianglamines can be synthesized, research groups have studied the trianglimines and trianglamine metal complexes for their catalytic behaviour in both bioorganic and bioinorganic chemistry, to mimic the enantioselective catalysis of natural enzymes.\(^{42-43}\)

Most of the reported trianglamine-metal complexes were synthesized starting from the calixsalens.\(^{44}\) Calixsalens are interesting due to their cavity and non-polar upper and polar lower rim (similar to calixarenes) and unlike other trianglamine derivatives. Because of its unique conformations and packing modes (Figure 6), calixsalens and its metal complexes have attracted a lot of attention.

*Figure 5. Pre-functionalization approach for trianglamine synthesis.*\(^{38}\)
Figure 6. a) General structure of calixsalen 1 and b-d) possible types of host packing in calixsalen crystals: tail-to-tail dimer (A), capsule (B) and putative structure of an hourglass dimer (C).\textsuperscript{29-30}

1.3.1 Copper Coordinations

Cu(II) complexes attract attention as magnetic materials and systems that mimic the trinuclear copper sites in metalloenzymes such as multicopper oxidases (MCO’s). The trinuclear sites MCO’s carry out the reduction of oxygen to water.\textsuperscript{45-46}

In 2009, Lloret reported one of the first examples in which Cu\textsubscript{3}(OH)\textsubscript{2} ensemble is formed within a nonaaza-macrocycle (trianglamine).\textsuperscript{47} Nonaaza-macrocycle are trianglamine derivatives consists of three (R,R)-1,2-diaminocyclohexane residues linked through 2,6-dimethylpyridine spacers. They reported on its crystal structure, magnetic behaviour, and characterization in solution.\textsuperscript{47}

In 2012, Lisowski reported the synthesis and characterization of new trinuclear Cu(II) complexes with enantiopure calixsalen derived from 2,6-diformyl-4-methylphenol and (1S,2S)-1, 2-diaminocyclohexane.\textsuperscript{48} Calixsalens provide a N\textsubscript{2}O\textsubscript{2} binding site for each Cu(II) ion. Each copper site comprises of two amine nitrogen atoms from the
diaminocyclohexane ring and two oxygen atoms from adjacent deprotonated phenol groups. In addition to the three phenolate oxygen atoms bridging each Cu(II) pair, the Cu1–Cu2 pair is also bridged by the chloride anion. Each of the Cu(II) ions exhibit different geometries (Figure 7).

![Figure 7](image)

*Figure 7. Cu₃(OH)₂ formed within nonaaza-macrocycle (trianglamine).*\(^{47}\) Trinuclear Cu(II) complexes crystallization with trianglamine.\(^{48}\)

### 1.3.2 Nickel Coordinations

In 2005, Gao reported mono-, di-, tri- and tetranuclear chiral macrocyclic Ni(II) complexes starting from chiral calixsalen macrocycles.\(^{43}\)

Again in 2016, a dinuclear Ni(II)-calixsalen complex was studied and its structure and magnetic properties were reported in effort to better understand chiral multinuclear sites to simulate and understand the behaviour of metalloenzymes.\(^{49}\)

### 1.3.3 Zinc Coordinations

In 2016, Lisowski reported that calixsalen forms an interesting trinuclear complex with Zn(II).\(^{28}\) In these compounds, two deprotonated macrocyclic units are connected by the Zn(II) metal ions to form the cage-like molecule [Zn₃L₂] (see Figure 8 and Figure 2).
The complex resembles larger metal-seamed nanocapsules based on two pyro-gallol[4]arenes connected by Zn(II) ions.

Scheme 2. Calixsalen and Zn(II) forming a trinuclear container-like complex \([\text{Zn}_3\text{L}_2]\), where L is calixsalen.\(^{28}\)

Figure 8. Molecular structure of calixsalen grown from EtOH/DCM.\(^{28}\)

These compounds are attracting increased attention as hosts for various guest molecules. Despite the small volume of the interior of \([\text{Zn}_3\text{L}_2]\) complexes, which limits the number of potential organic guests, their container-like shape makes them suitable for gas capture as they are able to maintain their intrinsic microporosity upon guest removal.

The tert-butyl derivative of this calixsalen Zn complex exhibits remarkable gas-sorption properties and a gate-pressure effect unique for POM’s. They found that the
gas sorption of the methyl derivative zinc complex was negligible compared to the tert-butyl derivative, despite the similar molecular structures of these two complexes (see Figure 9). In this paper, they suggest that difference arises from the different packing arrangements of individual cage molecules in their respective crystals.

![Figure 9. Methyl derivative and tert-butyl derivative.](image)

1.3.4 Lanthanide Coordinations

Lanthanide(III) complexes of calixsalen have also been described. The synthesis of complexes of these ligands containing more than one lanthanide(III) or yttrium(III) ions, within the macrocycle cavity, have similarly been studied.

![Figure 10. Nd(III) ion gives two trinuclear macrocyclic units bridged by hydroxide anions.](image)
X-ray crystal structures of the Nd(III), Sm(III), Gd(III), Dy(III), and Y(III) complexes reveal trinuclear complexes with Ln(III) ions bridged by the phenolate oxygen atoms of the calixsalen as well as by hydroxo-bridges.

Many of these enantiopure Ln-calixsalen complexes have been explored for their magnetic characteristics and their possible applications as single molecule magnets.\textsuperscript{50-51}

1.4 Conclusion

To date, trianglamine derivatives have been explored mostly as metal complexes for their application as biomimetic metalloenzymes.\textsuperscript{42-43} Despite recent gas adsorption studies,\textsuperscript{52} supramolecular trianglamine assemblies and trianglamine-metal coordination complexes are still relatively unexplored for their application as POM’s for gas and molecular separations. After the research we conducted, we came to realise that there is a need to design porous materials with intrinsic porosity (shape-persistent voids) as they tend to have superior BET surface areas in comparison to materials which contain extrinsic pores exclusively.\textsuperscript{11} For this reason, trianglamines appear useful due to their intrinsic unique triangle-shaped pores, with the likelihood of additional extrinsic pore formation upon assembly.

As was said by Olson, \textit{et. al.} “However, the trianglimine macrocycle as a scaffold upon which to build increasingly complex functional molecular structures and superstructures, has not yet reached its full potential.”\textsuperscript{36} Although they were referring
to the non-reduced trianglamine precursor, we believe this is still relevant for trianglamine and we think that trianglamine has yet a key role to play in the field POM’s. For this reason, this project was created to explore trianglamines and its metal complexes as new potential macrocycles and POM’s for gas storage and separation processes.
2. EXPERIMENTAL SECTION

2.1 General Methods

All solvents and reagents were obtained from commercial sources (unless stated otherwise) and used without any further purification. The preparation of moisture and air-sensitive materials were carried out in flame-dried flasks under inert atmosphere by using Schlenk lines. $^1$H and $^{13}$C NMR were carried out using 400 MHz, 500 MHz and 600 MHz Bruker spectrometers. Chemical shifts (δ) are reported in parts per million (ppm) relative to traces of solvent in the corresponding deuterated solvent.

2.2 Synthesis and Characterization of Trianglamines

2.2.1 Synthesis of Trianglimine and Trianglamine (T)

Terephthalaldehyde (1.17 g, 8.76 mmol, 1 eq.) was stirred in methanol until completely dissolved. (±)-trans-1,2-diaminocyclohexane (1 g, 8.76 mmol, 1 eq.) was then added to the stirring solution, followed by triethylamine (21.89 mmol, 3 mL), and the solution was left stirring overnight to form trianglimine. A pale-yellow precipitate was formed. NMR chemical shifts are as described in previous publications.$^{1, 40-41}$
The trianglimine was reduced *in-situ* with sodium borohydride (26.78 mmol, 1 g, 3 eq.). The solution was first cooled in an ice bath and the sodium borohydride was added over one hour. After the solution was left stirring for a further four hours the solvents were removed in vacuo and the residue was extracted with dichloromethane and sodium carbonate (5%). The organic phase was dried over sodium sulfate and evaporated to form T. The yellow solid yielded was stored under vacuum.

**Purification:** The solids were dissolved in ethanol (15 mL) and a mixture of conc. HCl (3.5 mL) in ethanol (7 mL) was slowly added to the product solution. Upon addition, an off-white precipitate was obtained which was filtered, washed with ethanol and dried. The dried precipitate was then solubilized in water and a 2M NaOH solution was added dropwise to form a white precipitate. The precipitate was filtered, washed with water and dried to yield purified T. 89% yield.

**1H NMR** (CDCl₃): δ = 1.08-1.24 (m, 2H, CH₂), 1.68 (br, 2H, CH₂), 2.32 (m, 1H, CH-N), 3.6-3.96 (dd, 2H, CH₂-N), 7.33 (d, 2H, Har).

**13C NMR** (CDCl₃): δ = 25.12 (CH₂), 31.47 (CH₂), 50.53 (CH-N), 60.51 (CH₂-N), 128 (CH₃), 139.4 (Car)

**HRMS** m/z found for C₄₂H₆₀N₆ 649.4910 [M+1], calculated C₄₂H₆₀N₆ 648.49
2.2.2 Synthesis of isoTrianglimine and isoTrianglamine (T_{iso})

Procedure based on Trianglimine synthesis. Isophthalaldehyde (1 g, 8.76 mmol) was used in the place of terephthalaldehyde and the trianglimine synthesis procedure was repeated.

Reduction of the isoTrianglimine is identical to the procedure for the reduction of Trianglimine. Reduction afforded an off-white solid.

The solid was reprecipitated in acetonitrile, filtered and washed with acetonitrile and dried to obtain a white solid. T_{iso} was obtained with a yield of 52%.

**\( ^1H \text{ NMR} \) (CDCl\(_3\)): \( \delta = 1.27 \) (m, 4H), 2.46 (d, 2H, CH-N), 2.74 (bm, 2H, N-H), 3.75 (dd, 4H, CH\(_2\)-N), 7.13 (d, 2H, CH\(_{ar}\)), 7.24 (t, 1H, CH\(_{ar}\)), 7.72 (s, 1H, CH\(_{ar}\)).

**\( ^{13}C \text{ NMR} \) (CDCl\(_3\)): \( \delta = 25.12 \) (CH\(_2\)), 31.48 (CH\(_2\)), 51.19 (CH-N), 61.35 (CH\(_2\)-N), 126.67-127.85 (CH\(_{ar}\)), 141.11 (q, C\(_{ar}\))

**HRMS** m/z found for C\(_{28}\)H\(_{40}\)N\(_{4}\) 433.3315, calculated for C\(_{28}\)H\(_{40}\)N\(_{4}\) 432.33

2.2.3 Synthesis of hydroxy-Trianglimine and hydroxy-Trianglamine (T_{OH})

Procedure based on Trianglimine synthesis. 2-hydroxyisophthalaldehyde (1.32 g, 8.79 mmol, 1 eq.) was used in the place of terephthalaldehyde reacted with the diaminocyclohexane (1 g, 8.76 mmol, 1 eq.), and the trianglimine synthesis procedure was repeated.
Reduction of the hydroxy-Trianglimine is identical to the procedure for the reduction of Trianglimine. Reduction afforded a yellow solution. The product was extracted using water and dichloromethane. The organic phase was then dried over sodium sulfate, and the solvent removed to obtain ToH.

The solid was reprecipitated in acetonitrile, filtered and washed with acetonitrile to obtain a light-yellow solid, with a yield of 65%.

\(^1\)H NMR (d6-DMSO): \(\delta = 1.06-1.18\) (m, 4H, CH\(_2\)), 1.63-2.01 (d, 4H, CH\(_2\)), 2.23 (d, 2H, CH-N), 3.23 (bs, 1H, OH), 3.69 (dd, 4H, CH\(_2\)-N), 6.62 (t, 1H, CH\(_{ar}\)), 6.9 (d, 2H, CH\(_{ar}\))

\(^1\)C NMR (d6-DMSO): \(\delta = 24.72\) (CH\(_2\)), 30.63 (CH\(_2\)), 47.38 (CH-N), 60.46 (Ar-CH\(_2\)-N), 118.18 (CH\(_{ar}\)), 125.92 (CH\(_{ar}\)), 127.39 (CH\(_{ar}\)), 156.48 (C\(_{ar}\)).

HRMS m/z found for C\(_{42}\)H\(_{60}\)N\(_6\)O\(_3\) 697.47 [M+1], calculated for C\(_{42}\)H\(_{60}\)N\(_6\)O\(_3\) 696.47 m/z found for C\(_{28}\)H\(_{40}\)N\(_4\)O\(_2\) 465.32 [M+1], calculated for C\(_{28}\)H\(_{40}\)N\(_4\)O\(_2\) 464.32

2.2.4 Synthesis of pyridine-Trianglimine and pyridine-Trianglamine (T\(_{py}\))

Procedure based on Trianglimine synthesis. 2,6-Pyridinedicarboxaldehyde was used in the place of terephthalaldehyde and the trianglimine synthesis procedure was repeated. A pale-yellow solid was obtained after extraction in water and dichloromethane and dried yielding T\(_{py}\).
Reduction of the pyridine-Trianglimine is identical to the procedure for the reduction of Trianglimine. Reduction afforded an off-white solution. The product was extracted using water and dichloromethane. The organic phase was then dried over sodium sulfate, and the solvent removed to obtain T_{py}. The solid was reprecipitated in acetonitrile, filtered and washed with acetonitrile and to obtain a white solid.

\[ ^1\text{H NMR (d6-DMSO): } \delta = 7.84 \text{ (d, 2H, CH}_2\text{-N)}, 7.74 \text{ (t, 1H, CH}_2\text{ar)}, 3.50 \text{ (m, 2H, CH}_2\text{-N)}, 3.24 \text{ (m, 2H, CH}_2\text{-N)}, 2.16 \text{ (d, 2H, CH-N)}, 1.92 \text{ (m, 6H, CH}_2\text{)}, 1.53 \text{ (m, 4H, CH}_2\text{)} \]

\[ ^{13}\text{C NMR (d6-DMSO): } \delta = 24.3 \text{ (CH}_2\text{)}, 30.3 \text{ (CH}_2\text{)}, 70.9 \text{ (CH-N)}, 74.24 \text{ (CH}_2\text{-N)}, 121.9 \text{ (CH}_2\text{ar)}, 136.6 \text{ (CH}_2\text{ar)}, 160.7 \text{ (C}_\text{ar}) \]

### 2.3 Trianglamine-Metal Coordinations Complexes

#### 2.3.1 Copper (II) Coordination

[Cu\text{I}_\text{T}]: Trianglamine (10 mg, 0.015 mmol, 1 eq.) was solubilized in 1 mL of methanol. To this was added a dropwise solution of CuSO\text{4·5H}_2\text{O} (15.4 mg, 0.060 mmol, 4 eq.) in 2 mL of water. The mixture was left undisturbed, for four days at room temperature, yielding deep blue crystals.

[Cu\text{I}_\text{T}_{iso}]: isoTrianglimine (10 mg, 0.023 mmol, 1 eq.) was solubilized in 1 mL methanol. To this was added a dropwise solution of CuSO\text{4·5H}_2\text{O} (15.3 mg, 0.06 mmol,
2.67 eq.) in 2 mL of water. The mixture was left undisturbed, for four days at room temperature, yielding colourless crystals.

### 2.3.2 Zinc (II) Coordination

[Zn₂T₂]: Trianglamine (10 mg, 0.015 mmol, 1 eq.) was solubilized in 1 mL of methanol. To this was added a dropwise solution of Zn(NO₃)₂•6H₂O (18.4 mg, 0.060 mmol, 4 eq.) in 2 mL of water. The mixture was left undisturbed, for four days at room temperature, yielding colourless crystals.

[Zn₂Tᵢso]: isoTrianglimine (10 mg, 0.023 mmol, 1 eq.) was solubilized in 1 mL methanol. To this was added a dropwise solution of Zn(NO₃)₂•6H₂O (17.8 mg, 0.06 mmol, 2.67 eq.) in 2 mL of water. The mixture was left undisturbed, for four days at room temperature, yielding colourless crystals.

[Zn₆Tₚy₂]: pyridineTrianglimine (10 mg, 0.023 mmol, 1 eq.) was solubilized in 1 mL dichloromethane. To this was added a dropwise solution of Zn(NO₃)₂•6H₂O (18 mg, 0.06 mmol, 2.67 eq.) in 2 mL of methanol. The mixture was left undisturbed, for seven days at room temperature, yielding colourless crystals.
2.4 Aromatic Trianglamine

2.4.1 Synthesis of Ligand

Terephthalaldehyde (0.5 eq., 247 mg, 1.84 mmol) was added to a stirring mixture of phenylenediamine (1 eq., 400 mg, 3.77 mmol) in methanol (37 mL) and trimethylamine (1.4 mL, 2.5 eq.). The mixture was stirred at room temperature for about 18 hours. A deep orange precipitate formed, was filtered and washed with methanol. Yielding (116 mg, 20%).

$^1$H NMR ($d_6$-DMSO): $\delta =$ 5.28 (bs, 2H, NH$_2$), 6.58 (t, 1H, Car-H), 6.75 (d, Car-H, 1H), 7.00 (t, Car-H, 1H), 7.19 (d, Car-H, 1H), 8.11 (s, Car-H, 2H), 8.74 (s, CH-N, 1H).

$^{13}$C NMR ($d_6$-DMSO): $\delta =$ 49.05 (C-N), 115.25 (Car-H$_2$), 116.57 (Car-H$_2$), 117.41 (Car-H$_2$), 128.40 (Car), 129.25 (Car-H), 135.35 (Car-N), 139.06 (Car-H), 144.74 (Car-H), 155.92 (Car)

ESIMS m/z, calculated for C$_{20}$H$_{18}$N$_4$ 314.15 m/z, found 315.15.
Figure 11. $^1$H NMR (above) and $^{13}$C (below) (400 MHz, 298 K, CDCl$_3$) of Trianglamine, T.
Figure 12. $^1$H NMR (above) and $^{13}$C (below) (400 MHz, 298 K, CDCl$_3$) of isoTrianglimine [2+2], $T_{iso}$. 
Figure 13. $^1$H NMR (above) and $^{13}$C (below) (500 MHz, 298 K, $d_6$-DMSO) of hydroxyTrianglimine , T$_{OH}$.
Figure 14. $^1$H NMR (above) and $^{13}$C (below) (500 MHz, 298 K, CDCl$_3$) of pyridineTrianglamine, T$_{py}$
Figure 15. $^1$H NMR (above) and $^{13}$C (below) (500 MHz, 298 K, $d_6$-DMSO) of Ligand.
Figure 16. 2D-COSY of Ligand (500 MHz, 298 K, d6-DMSO).
CHAPTER 3:
3. RESULTS AND DISCUSSION

3.1 Synthesis and Characterization of Trianglamine

For this project, all trianglimines were reduced to their trianglamine counterparts and used for further studies in their reduced forms.

3.1.1 Synthesis of Trianglimine and Trianglamine

Scheme 3. Synthetic scheme for the formation of Trianglimine and the reduction to afford Trianglamine, T.

The trianglamine procedure referenced in the Experimental Section can easily be reproduced on a gram scale (repeated on two grams), and in the case of trianglamine, scheme 3, still resulting in >90% yield. This is a clear advantage of trianglamine, the ability to easily synthesize this chiral macrocycle, in one pot and two steps, in large amounts and under ambient conditions. This is the conventional procedure for trianglamine synthesis and it has been previously reported.\(^1\) To obtain a purified trianglamine, a 2-step wash is carried out. The crude is first dissolved in ethanol, and some concentrated acid solubilised in methanol is added dropwise to the trianglamine-ethanol solution. Hence, the amines are protonated, the salt is formed, and precipitated out of solution. Anything that can not be precipitated, i.e. not protonated, is left in the
ethanol solution and washed from the precipitate via filtration. The trianglamine salt is then solubilized in water and a 2M solution of sodium hydroxide is added to the trianglamine solution, dropwise, readjusting the pH, and reprecipitating the trianglamine. The trianglamine can then be washed with water and dried under reduced pressure (See Scheme 4).

Scheme 4. General purification steps for trianglamines.

The formation of the trianglimine can be clearly observed via NMR, due to the loss of the aldehyde signal at 10.14 ppm and the appearance of the signal at approximately 8.3 ppm indicating the formation of the imine bond. After reduction, the signal at 8.3 ppm corresponding to the imine bond disappears and a new signal appears at 3.4 ppm confirming that the imine bond has been reduced to form the trianglamine. The [3+3] product can then be confirmed through MS and SCXRD.

The trianglamine was crystallized from ethyl acetate and the resulting crystals were studied using SCXRD. SCXRD data confirms previously reported data of trianglamine crystallized from ethyl acetate (organic solvents).\(^\text{31}\)
Figure 17. a) Crystal structure of trianglamine b) crystal packing.

3.1.2 Synthesis of isoTrianglimine and isoTrianglamine

The isoTrianglimine was formed according to the same trianglamine procedure, using 1, 3-isophthalaldehyde as the dialdehyde, but the “purification step” was not carried out. The yield for this reaction was 52%. Initially it was assumed that upon completion of the reaction, that the [3+3] triangle-shaped macrocycle was achieved, but when mass spectrometry was carried out on the sample, a dominant peak at 434.33 m/z was observed. It was later realised that the [2+2] product had formed in this case, instead of the expected [3+3] product, which should have an expected molecular ion peak at 648.9 m/z.

This same reaction was repeated using the enantiopure, non-racemic form of the diaminocyclohexane, (1R,2R)-(+) diaminocyclohexane. The same procedure was repeated to yield a [2+2] product. We discovered a strange phenomenon with the racemic and non-racemic diaminocyclohexane. The racemic macrocycle was found to be completely soluble in organic solvents, in contrast to the non-racemic macrocycle, which was soluble in water. Hence, we tried to isolate the enantiomeric pairs of our...
racemic product via organic-aqueous phase separation (chloroform/water). From the NMR assignments, we observed that we had the presence of both [2+2] enantiomers in each phase. To the best of our knowledge, this phenomenon has not yet been reported with the [2+2] $T_{iso}$ macrocycles.

Figure 18. Molecules 1 synthesized from (±)-trans-1, 2-diaminocyclohexane whilst molecule 2 was synthesized with (1R, 2R)-diaminocyclohexane (enantiopure).

We successfully crystallized the $T_{iso}$ in dichloromethane with a few drops of diethyl ether, achieving single crystals. SCXRD was carried out on these crystals and the structure was obtained. We expected a close-packing network that would hopefully retain and align its cavity to form a tubular or channel like pore. Through the packing mode, it can be observed that the molecular units are not so closely packed (even though pi-pi stacking is present, see Figure 19.)
Figure 19. Ball and stick representation of crystal structure of T_{iso} a) molecule b) packing mode c) pi-pi interactions, with an intramolecular distance of 4.994 Å (hydrogen atoms and solvent molecules omitted for clarity).

These crystals were then submitted for gas sorption studies to test their gas uptake abilities. Unfortunately, no significant absorption was achieved for nitrogen.

Figure 20. Nitrogen sorption data of T_{iso} activated at 298K (black trace) and 318K (blue trace).

3.1.3 Synthesis of hydroxy-trianglimine and hydroxy-trianglamine

The hydroxy-trianglamine (calixsalen) was formed according to the same trianglamine procedure, using 2-hydroxyisophthalaldehyde as the dialdehyde, but the “purification step” was not carried out. The achieved trianglamine was suspended, filtered and
washed in acetonitrile. Similarly, the ToH formation could be identified using NMR. The hydroxyl group could be identified using NMR by the presence of a broad signal at around 3.3 ppm. Again, due to obtaining an NMR spectrum matching previously reported results, it was assumed that we had formed the [3+3] macrocycle. After MS, it was confirmed that we had synthesized a mixture of both the [2+2] and [3+3], due to the presence of the 465.31 m/z peak [M+1], corresponding to the [2+2] product, and the 697.47 m/z peak [M+1] and corresponding to the [3+3] product. Because of the symmetrical nature of both the [2+2] and [3+3] macrocycles, it can be deduced that NMR is not conclusive evidence to verify synthesis of a single macrocycle type.

Single crystals of ToH were obtained by crystallization in dichloromethane and SCXRD was carried out on the obtained crystals. We discovered that only the [2+2] macrocycle was present in the crystal structure (see Figure 22).

Figure 21. Experimental PXRD pattern of TOH (above) and simulated PXRD pattern of TOH [2+2] (below).
PXRD was carried out on our crude powder product, and this pattern was compared to the simulated PXRD pattern derived from the crystal structure of crystallized [2+2] T_{OH}. From this, we see that only some peaks were identical in both, and the PXRD of the crude powder T_{OH} product had a number of peaks unique to it. It can be suggested from both the evidence found in MS and PXRD, that a mixture of both the [2+2] and [3+3] macrocycle is present in the powder and crystallization in dichloromethane solely affords the [2+2] macrocycle.

![Figure 22. Ball and stick representation of crystal structure of T_{OH} [2+2] a) crystal structure b) crystal packing mode.](image)

Clearly shown from the crystal structure, we can see that unlike calixsalen, which has all the hydroxy groups on the lower rim of its vase-like structure (see Figure 6), T_{OH} [2+2] has one hydroxyl group pointing upwards, and the other pointing downward, an anti- conformation. The packing mode for T_{OH} was not a closely layered and tightly packed structure, but rather loosely packed. No strong intramolecular bonds were found between the molecules.

These T_{OH} crystals were also submitted for gas sorption testing. Unfortunately, no significant absorption was achieved for either nitrogen or carbon dioxide. This is probably owing to the packing of the structure. The T_{OH} would need to form some sort
of channel or cavity upon packing because the open window/pore of the T\textsubscript{OH} itself appears to be unable to retain gas molecules.

![Graph](image)

*Figure 23.* Nitrogen sorption data of T\textsubscript{OH} activated at 298K (black trace).

### 3.2 Trianglamine-Metal Coordination

Various metal complexes (M) were initially tested so that from the initial experiments and observations of crystal formation (which would hopefully indicate stability of the material formed) or lack thereof, we would be able to short list the metal complexes we would use to carry out the remainder of our study. The initial “trial” study was conducted on ten different metal complexes at two different molar equivalents. Trianglamine was set at one molar equivalents (10 mg) and the metal complexes at both two and four molar equivalents. On the basis of these experiments, 3 metal complexes were selected.
Table 1. Initial trial experiments with various Metal complexes (M) described in 1-8, coordinated with T

<table>
<thead>
<tr>
<th></th>
<th>2 equivalents M</th>
<th>3 equivalents M</th>
<th>4 equivalents M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Zn(O2CCH3)2•2H2O</td>
<td>No crystals</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>Zn(NO3)2•6H2O</td>
<td>No crystals</td>
<td>-</td>
</tr>
<tr>
<td>3.</td>
<td>Zn(C5H7O2)x•xH2O</td>
<td>No crystals</td>
<td>-</td>
</tr>
<tr>
<td>4.</td>
<td>FeSO4•7H2O</td>
<td>No crystals</td>
<td>-</td>
</tr>
<tr>
<td>5.</td>
<td>(NH4)2Fe(SO4)2•6H2O</td>
<td>No crystals</td>
<td>-</td>
</tr>
<tr>
<td>6.</td>
<td>Ni(OCOCH3)•4H2O</td>
<td>No crystals</td>
<td>-</td>
</tr>
<tr>
<td>7.</td>
<td>Ni(C5H7O2)2•5H2O</td>
<td>No crystals</td>
<td>-</td>
</tr>
<tr>
<td>8.</td>
<td>CuSO4•5H2O</td>
<td>CRYSTALS</td>
<td>-</td>
</tr>
<tr>
<td>9.</td>
<td>CuSiF6</td>
<td>-</td>
<td>powder</td>
</tr>
<tr>
<td>10.</td>
<td>NiSiF6•6H2O</td>
<td>-</td>
<td>powder</td>
</tr>
</tbody>
</table>

Figure 24. Trianglamine derivatives on which metal coordination studies were carried out.
3.2.1 Copper (II) Coordination

A series of crystallization experiments were carried out on trianglamine derivatives (Figure 24) to determine some standard conditions for Copper (II) coordination and for the formation of good quality crystals. All copper crystallizations were carried out on one equivalent of the trianglamine, solubilized in 1 mL of methanol, except for Tpy which was solubilized in DCM. Metals were used in two, three and four equivalents and solubilized in water.

Coordination experiments were carried out using CuSO₄•5H₂O as a metal complex at room temperature. Crystals were yielded for three of the trianglamine derivatives with two and four equivalents of CuSO₄. For the two equivalent CuSO₄ experiment, crystals yielded after storage over two days at room temperature.

From the crystal structure, we can deduct that Tiso [2+2] forms a dinuclear complex with Cu(II). Tiso [2+2] provides a N₂ binding site for each Cu(II) ion. Each copper site comprises two amine nitrogen atoms from the diaminocyclohexane ring and three oxygen atoms from the sulphate ion (Figure 25).
When trianglamine is coordinated with Cu(II), Figure 26 a), it forms a trinuclear complex. T provides a N₂ binding site for each Cu(II) ion. Each Cu ion is linked to three oxygen atoms. These oxygen atoms act as bridges to connect to other Cu ions, bound to other trianglamines. Out of the three Cu coordination sites on one T molecule, two coordination sites are involved as bridges to link with another T molecule. In this way, T forms a “coordination-like polymer” with Cu(II). Unfortunately, this T-Cu(II) has no significant nitrogen adsorption properties and it has yet to be tested for carbon dioxide adsorption.

![Figure 26. a) Crystal structure of trianglamine complexed to CuSO₄ b) packing mode of trianglamine CuSO₄ complex.](image)

**Figure 27.** Nitrogen sorption plot of trianglamine CuSO₄ complex. T activated by acetonitrile at 298K (black trace) and by acetonitrile at 313K (blue trace). T activated by methanol at 298K (green trace) and by methanol at 313K (pink trace).
3.2.2 Zinc (II) Coordination

A series of crystallization experiments were carried out on trianglamine derivatives to determine some standard conditions for Zinc (II) coordination, and for the formation of good quality crystals. All zinc crystallizations were carried out on one equivalent of the trianglamine, solubilized in 1mL of methanol, except for Tpy which was solubilized in DCM. Metals were used in both two and four equivalents and solubilized in water.

Coordination experiments were carried out using Zn(NO$_3$)$_2$$\cdot$6H$_2$O and Zn(C$_5$H$_7$O$_2$)$_2$$\cdot$xH$_2$O as metal complexes at room temperature. Crystals were yielded for T, Tiso, and Tpy derivatives with four equivalents of Zn(NO$_3$)$_2$. No coordination occurred with TOH or for any of the derivatives with Zn(C$_5$H$_7$O$_2$)$_2$. The crystals formed with Zn(II) were characterised using SCXRD.

Tpy coordinates with Zn(II) to form a very interesting complex with an intriguing geometry. Tpy coordinates with Zn(II) forming a "cage-like" star with an intrinsic pore.

Figure 28. Tpy and zinc(II) coordination. Star like geometry a) crystal structure of Tpy-Zn(II) b) crystal structure depicting cavity/pore of “cage-like” star c) packing mode. Hydrogen atoms omitted in images a) and c)
In a single unit of this cage, there are six Zn ions. Each Zn is coordinated to the N atom on the pyridine and to two amino groups, one amino group of the cyclohexane ring, on neighbouring sides of the pyridine. It is still largely unclear to us how the [3+3] macrocyclic T\textsubscript{py} forms such a structure in the presence of Zn(II). From the crystal structure, it does not appear to be a dimer, but rather a [6+6] macrocycle coordinating with the Zn ions. From the MS of the starting materials, we are unable to detect the presence of a [6+6] macrocycle. From the T\textsubscript{py} NMR (Experimental Section) it is clear there is a mixture of products formed. After MS verification we realised that we had formed the [2+2] non-reduced macrocycle as the major product and not the [3+3] as thought. In 2014, a paper reported the phenomenon of the [2+2] pyridine macrocycle rearranging in the presence of a template metal ion.\textsuperscript{53} In this paper, they report that the non-reduced form of the [2+2] macrocycle is able to undergo rearrangement to a [6+6] macrocycle in the presence of the cadmium(II)chloride. The imine bond is reversible so in the presence of a metal ion, it is able to revert and rearrange. We believe that this is what we are observing in our complex. In order to prove this why are looking to purify our T\textsubscript{py} [2+2] macrocycle and repeat the coordination.

Despite the inner cavity of this cage-like star, no significant nitrogen sorption was achieved.
Figure 29. Nitrogen sorption plot of pyridine-Trianglamine and Zn(II) complex. Activation carried out at 298K (black trace) and activation carried out at 313K (blue trace).

Trianglamine also coordinates with Zn(II) to form a dimer complex. In one unit, two trianglamine molecules are directly coordinated with two Zn ions. One Zn ion binds to a pair of N atoms of the diaminocyclohexane ring, and is bridged by two oxygen atoms of another Zn bound to another trianglamine molecule.

Figure 30. a) Crystal structure of trianglamine coordinated to Zn, side-view b) top-view.

T_{iso} also forms a coordination complex with Zn(II) but does not coordinate to form a more complex structure. Rather T_{iso} remains as individual units, with a Zn ion binding at each diamino-site of the T_{iso}. 
3.3 Functionalization of Trianglamine

There is a need to design porous materials with intrinsic porosity (shape-persistent voids) as they tend to have superior BET surface areas in comparison to materials which form extrinsic pores. For this reason, trianglamines appear useful due to their intrinsic triangle-shaped pores, and with successful manipulation, they can be suitable precursors for supramolecular assembly that can potentially form extrinsic porosity upon assembly.

Functionalization of the aryl moiety of the aldehyde, before trianglamine synthesis, has previously been considered. Recently, a group reported some novel aryl functionalized trianglamine derivatives. They stated that “alkylating the amine nitrogen atoms could otherwise potentially hinder their later use as metal coordination sites.” But, depending on the application, this statement can be irrelevant. Functionalization on the aryl moieties blocks the intrinsic pore/window of the trianglamine hence limiting their use as a porous organic material (see Figure 32).
Figure 32. Aryl functionalized trianglamine derivative, reported by Olson et. al.\textsuperscript{36}

Scheme 5. General steps involved in reduction of NH moiety of trianglamine.

The reduction of the amino-moieties of trianglamine structures to promote supramolecular assemblies has not yet been reported. Upon research, we found that reduction had been carried out on the 6 amino groups using acyl chlorides in 2006\textsuperscript{37} but since no further study was done on them. Additionally, their structures were not manipulated for any type of supramolecular assemblies. Therefore, groups with strong hydrogen donating and accepting capabilities, and aromatic systems can be utilized to favour the formation of these assemblies such as carboxylic acids or hydroxyl moieties. For this reason, NH-functionalized trianglamines with functionalities that promote hierarchal assembly, were attractive to us.
Many synthetic routes were attempted to carry out the reduction of the amino-group on the trianglamine (see Figure 33, route A), all of them appearing to have failed when characterized by NMR, falsely deduced due to very broad NMR signals. It was later realised that the successfully reported NH-functionalized trianglamines were verified via MS as they also reported broadened $^1$H signals due molecules of this nature. $^{37-38}$

It was also mentioned in one of these reports, that cooling down the NMR instrument to lower temperatures (273 K) could significantly resolve the $^1$H NMR signals. $^{38}$ This is probably due to the conformational flexibility of the trianglamine, especially the increased number of rotational bonds upon NH-reduction. Therefore, lower temperatures can limit the flexibility of the molecule, achieving a better resolved $^1$H NMR. Despite the number of scans for the $^{13}$C NMR, no signals were seen.

Figure 33. Different routes were attempted to achieve functionalized trianglamine.
Figure 34. $^1$H NMR of trianglamine reduced by cinnamoyl chloride in CDCl$_3$.

Figure 35. Stacked 1H NMR traces of starting materials, cinnamoyl chloride (blue trace), trianglamine (green trace), and final product (maroon trace).
It was decided to limit the factors that were possibly influencing the “failure” of the NH-reduced trianglamine by using a commercially available acyl chloride, cinnamoyl chloride, and by repeating the procedure in completely anhydrous conditions (see Figure 33, route B). Again the NMR signals were quite broad, making it difficult to deduce whether product formation had occurred or not. This time, MS was carried out on the sample to confirm if we had achieved the NH-reduction on the 6 amino groups of the trianglamine with cinnamoyl chloride. Through MS, we could confirm that certainly, the reduction had been successful. Due to the difficulty of isolating this product through Preparative Thin Layer Chromatography, this side-project, 'NH-functionalization of trianglamine' was discontinued.
3.4 Aromatic Trianglamine

Trianglamine derivatives explored up to date are [3 + 3] cyclocondensations between a diamino cyclohexane (non-aromatic) and an aromatic dialdehyde. With these conventional trianglamines, there are a limited number of methods that can be used to functionalize them and hence limited manipulation of their chemistry. With conventional trianglamine, the organic linker can only be varied slightly to yield a novel trianglamine derivative or precursor for supramolecular assemblies. On the contrary, with a fully aromatic system, functionalization can be built in before trianglamine synthesis along with the more challenging, post-functionalization approach. For example, by using a substituted aromatic diamine, there is an ability to manipulate trianglamine for self-assemblies and covalent or non-covalent frameworks (Scheme 6). Very few successful examples of synthesized aromatic “trianglamine” have been reported.54-55

Scheme 6. Proposed schematic plan for pre-functionalization of aromatic diamine for the formation of a COF.
Before embarking on building a pre-functionalized aromatic trianglamine, it was decided to synthesize the aromatic trianglamine from the less substituted phenylenediamine, and to establish a procedure. Once the necessary procedure and conditions could be optimised, then a pre-functionalized phenylenediamine could be used to build an aromatic trianglamine of greater complexity for various applications.

Three aromatic trianglamine procedures were attempted:

Firstly, the conventional trianglamine procedure conditions (detailed in the Experimental Section) was attempted for the aromatic trianglamine synthesis. Terephthalaldehyde was added to a stirring mixture of phenylenediamine in methanol and triethylamine. The mixture was stirred at room temperature overnight. This first reaction carried out was not at a 1:1 molar equivalent of phenylenediamine to terephthalaldehyde and hence an aromatic trianglamine could not have resulted, but rather a partial product that we have named ‘ligand’ (see Figure 15 and Figure 37) due to the 2:1 ratio of phenylenediamine to terephthalaldehyde. This ligand is particularly interesting due the four N atoms and hence its ability to coordinate with metal. We believe this ligand could be useful for the synthesis of some metallo-organic cages or further reacting it to build larger macrocycles.

Figure 37. a) Ligand b) aromatic trianglimine c) aromatic trianglamine.
The second procedure attempted was the reported procedure by Shionoya et al. Working under completely anhydrous conditions, a mixture of terephthalaldehyde in anhydrous THF was added to a stirring mixture of phenylenediamine in anhydrous THF. The resulting mixture was stirred at 50°C, under inert conditions, for 24 hours.

The final procedure attempted was again, the conventional trianglamine procedure conditions (detailed in the Experimental Section), but this time the molar ratio was adjusted to a 1:1 ratio. Terephthalaldehyde (1 eq., 496 mg, 3.7 mmol) was added to a stirring mixture of phenylenediamine (1 eq., 400 mg, 3.7 mmol) in methanol and trimethylamine (3 eq.). The mixture was stirred at room temperature overnight to yield aromatic trianglimine. This could be confirmed by NMR through the loss of the aldehyde signal at 10.15 ppm in d6-DMSO and the appearance of the imine signal at 8.63 ppm in CDCl3.

*Figure 38. a) Crystal structure of ligand b) packing mode of ligand.*
CHAPTER 4:
4. CONCLUSION

In the last 10 years, trianglamines have been well-studied due to their triangular shape and ability to coordinate different metals. Indeed, varieties of complexes bearing different trianglamines moieties as ligands were achieved as mono, di, and high-nuclearity metallo-macrocyle chiral systems. They have been well-exploited for their catalytic properties and their magnetic properties, in the case of copper. As presented, gas adsorption properties have not been fully explored. The goal of this project was to study the gas properties of the different complexes obtained with copper, zinc and platinum.

It remains unclear to us why all our synthesized trianglamine derivatives and trianglamine-metal coordination complexes display such poor gas sorption properties.

We hypothesize that the issues stem from two main reasons:

1. The lack of alignment of the pore/windows of the trianglamine, even with the presence of metal ions, the crystal structure reveals a misalignment of the windows in almost all cases.

2. A possible collapse of structure post-activation. Trianglamines are very hygroscopic materials, binding tightly to water molecules. We believe that upon activation, the exchange and removal of water disrupts and distorts the trianglamine structures, rendering them incapable of gas adsorption. To prove this, SCXRD would be needed to be repeated after the activation process.

Moving forward, we believe trianglamine can possibly achieve competitive gas adsorption capabilities due to the chemical nature of its pore, i.e. six nitrogen atoms, and unique gas sorption capabilities due to its distinctive pore shape. We believe the
key to harnessing these virtues would be to find a way to align the pores of the macrocycle, which is something we were unable to achieve throughout this project. Although our attempts to functionalize trianglamine were largely unsuccessful, successful functionalization with moieties that promote assembly could create a superstructure with retained “channel-like” porosity.
CHAPTER 5:
5. OUTLOOK

The trianglamine derivatives and trianglamine-metal coordination complexes that were synthesized throughout this project were found to have very poor gas sorption properties. We believe that although unsuitable for the aforementioned application, these macrocycles and metal complexes could have interesting applications in fields such as catalysis, drug delivery or as chiral receptors. Below we document the current projects that some of the materials synthesized are involved in:

Polyoxometalates

Polyoxometalates are polyatomic anions containing transition metal anions with oxygen ligands and are linked together by shared oxygen atoms to form discrete 3D-networks. Polyoxometalates form very rigid structures due to their relatively strong metal-oxygen coordination bonds. For this reason we seek to crystallize trianglamines with these polyoxometalate wheel structures,\textsuperscript{56} see Figure 39.

We hope that crystallization with these structures would yield a structure with assembled (micro)porosity of the trianglamine, similar to that depicted of in Figure 40, i.e. where the pores of the trianglamine would be aligned. Due to the solubility of the T\textsubscript{iso}[2+2] in aqueous medium, we have first attempted to crystallize it with the polyoxometalate wheel. Studies are still ongoing.
Figure 39. Typical polyoxometalate structures and wheel structure in red.\textsuperscript{56-57}

Figure 40. a) depiction of complexation of cyclodextrin (orange capsule) with polyoxometalate b) crystal structure of complexation.\textsuperscript{58}
**Protein delivery systems**

Recently, it was reported that a MOF was used to encapsulate and deliver CRISPR/Cas9 and enhance its endosomal escape so as to reach the nucleus of the cell.\textsuperscript{59} Imidazole along with Zn ion was combined with the protein to create a protein encapsulated-MOF, \textit{Figure 41}.

\textit{Figure 41}. Imidazole along with Zn ion was combined with the protein to create a protein encapsulated-MOF.\textsuperscript{59}

The small cavity size of T\textsubscript{iso} [2+2], 2.46Å, makes it suitable for biological applications such as drug and small molecule delivery. Also, due to the chirality of the system and the four nitrogen atoms present in the cavity, this therefore makes it attractive as a receptor and binding site for small molecules. We are now attempting to see if T\textsubscript{iso} [2+2] will assemble around a protein or small molecule in the presence of a metal ion and see if it can be used as a small molecule delivery system. Studies are still ongoing.
CHAPTER 6:
6. REFERENCES


42. Byun, J. C.; Lee, N. H.; Mun, D. H.; Park, K. M., Synthesis and characterization of dinuclear copper(II) complexes, [Cu-2([20]-DCHDC) (L-a)(2)] (L-a = N-3(-), NCS


