A SYNOPSIS

of the thesis entitled

Design, Synthesis and Tuning of Metallogel Properties and Their Application

to be submitted

for the award of the degree of

DOCTOR OF PHILOSOPHY

in

CHEMISTRY

by

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SYNOPSIS OF THE THESIS

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Research Student	—	**ADITYA ANIL PURANIK**
Title of Thesis	—	**Design, Synthesis and Tuning of Metallogel Properties and their Applications**
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The study of supramolecular metallogels formed by well-defined metallogelators has emerged and gained momentum since last decade. These systems have distinct advantages over the polymer gels or those formed by small organic molecules. The present study is with an intention to gain insights into the exciting field of supramolecular metallogels and explore their applications. The work in the thesis will be presented in the form of following chapters:

Chapter 1
Introduction

Chapter 2
Design, synthesis and birefringent properties of hydrogels derived from complex metallogelator containing copper(II), 2,2'-bipyridine and myo-inositol

Chapter 3
Investigating the effect of counter anions, terminal ligands and pH on gel formation and their use in designing metallogels

Chapter 4
Synthesis of metallogels of tricopper complex, $[Cu_3(bipy)_3(ins)]X_3$, with carbonate base and their application as heterogeneous catalysts for oxidation of phenols

Chapter 5
Effect of capping agents on gel formation and uptake of organic solvents by metallogels derived from 1,10- phenanthroline containing tricopper (II) complex

Chapter 6
DNA & BSA binding, superoxide dismutation, antimicrobial activity and cytotoxicity of copper(II) containing metallogelator complexes

Summary

INTRODUCTION

Introduction to gels

The term gel was coined by a Scottish chemist Thomas Graham. According to IUPAC, gel can be defined as a nonfluid colloidal network or polymer network that is expanded throughout its whole volume by a fluid. It is a heterogeneous system which consists of immobile network of solid gelator and a mobile solvent trapped within. Gel has solid-like property that is it can sustain shear stress.At the gelation point an infinite cluster is created that spans the whole system. One more important property characteristic to the gels is the sol-gel transition temperature (T_{gel}).[1]Sol-gel transition is the temperature at which macroscopic properties of the gel changes abruptly from solid-like gel to an isotropic liquid.

Classification of gels

The gels can be classified on the basis of source as **artificial** or **natural** gels. Another way of classifications on the basis of the medium as **organogels**, **hydrogels** or **aerogels**. They can also be classified as **chemical** gels or **physical** gels on the basis of types of interactions present.

Physical gels are composed of a gelator and the solvent which is entrapped by the gelator. It also has a third component which has no chemical interaction with the gelator, but it affects the properties of the gel (rheological properties, T_{gel}). The gelator is capable of forming the gel by itself. The third component does not play any role in gelation, it only modifies or affects the properties of the gel.

Composite liquid crystalline physical gel of photochromic azobenzene moieties as gelators and typical rod-like liquid crystalline (LC) molecules like 4-butyl-4'-cyanophenylas a third component has been reported.[2]It is a hybrid or composite gels because it has the combined properties of both: the gelator as well as the LC molecules.

Chemical gels are the ones in which 2 or more components react chemically to form a gelator which forms gel.

A bis(pyridylurea) ligand forms metallogels in methanol in the presence of up to 0.5 equivalent of copper(II) chloride.[3] Properties of the gel depend on the type of counter anion and the concentration of Copper ions. Gelation is favored by the presence of counter anions like chloride whereas nitrate and sulphate hinder the process of gel formation. Also, the T_{gel} temperature increases with the increase in the concentration of copper(II) chloride.

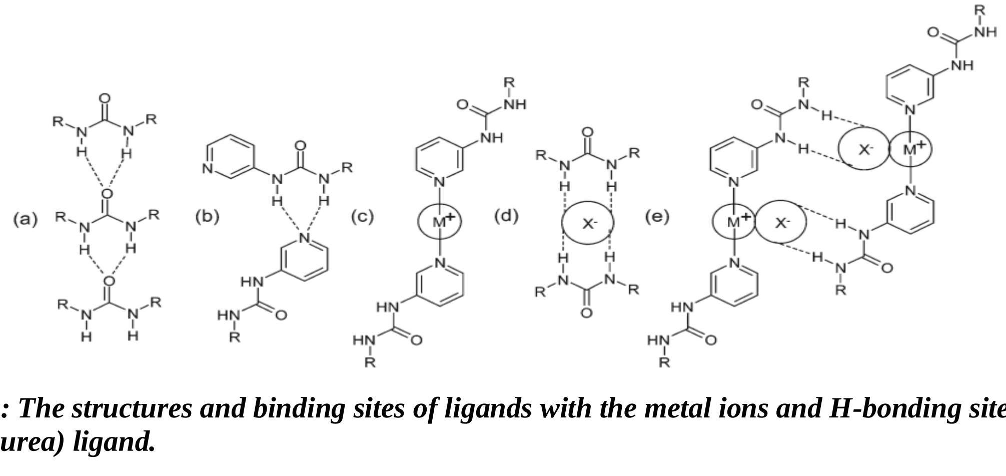


Figure 1.2: The structures and binding sites of ligands with the metal ions and H-bonding sites in bis(pyridylurea) ligand.

Metallogel formed by a methanolic solution of $NiCl_2.6H_2O$ with N-methylmorpholine has been reported.[4]Ag(I)–melamine coordination polymer which forms a metastable hydrogel at 1:1 molar ratio and 1:2 molar ratio has also been reported. The gel exhibits chiral behavior owing to the helical nature of the assembly.[5] Both these gels are chemical gels as there is chemical interaction between the metal and the ligand.

Advantages of Low-molecular weight gelators (LMWGs) over traditional & polymer gels
Polymer gels or metal oxide gels like silica gel find applications in very limited areas as they are rigid, more like solid and it is usually very difficult to attain the sol-gel transitions in these types of gels. As a result their main uses have been limited to absorbents or hydrogelators. Whereas on the other hand, supramolecular assemblies that result into gels are governed or held together by non-covalent interactions like H-bonding, π-π stacking, coordinate covalent bonds etc. As the extent of these non-covalent interactions can be controlled it is possible to tune the properties of the gels and design them for specific uses. Most of the LMWGs are biocompatible molecules. This gives the low-molecular weight gelators an advantage when it comes to biological applications. As the molecules are small having low-molecular weights their degradation becomes easy and so they are expected to have fast metabolic rates. These gels are highly stimuli responsive (pH, temperature, solvent and radiation) which make them suitable candidates for various other applications.

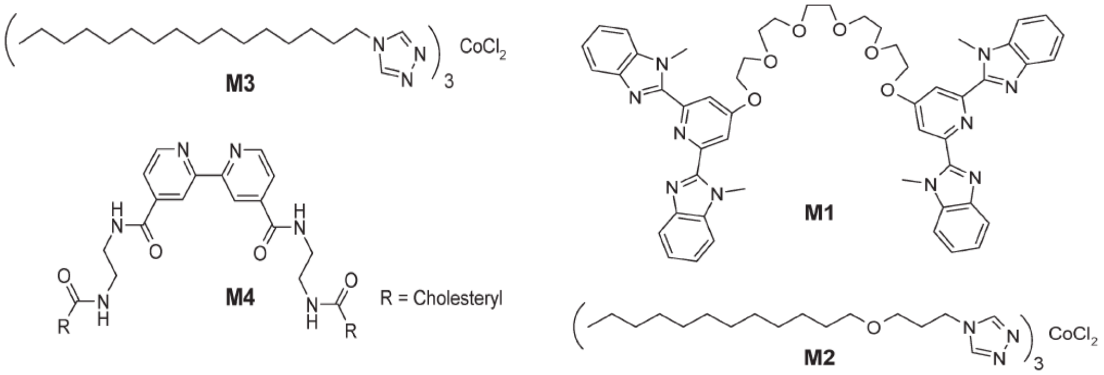


Figure 1.3: Molecules that have been reported to form metallogels.[6]

Advantages of incorporating metal ions in the gel

Metal ions form coordinate covalent bonds which are the strongest non-covalent interactions known, these interactions are capable of holding the supramolecular assembly together. Each metal ion has specific coordination geometry, thus assemblies with different morphologies can be designed. Metal ions can result into C_3symmetric complexes with some appropriate ligands like bipyridyl, phenanthroline etc. These C_3 symmetric complexes are expected to show chiral behavior. Thus, the gels formed using such complexes can exhibit interesting optical and birefringent properties. Metal ions can also have an effect on the T_{gel} temperature of the gels. Thus, the tuning of the sol-gel transition temperature is possible by varying the concentration of metal ions. Metallogels synthesized using transition metal ions can show interesting magnetic and redox properties.

Applications of gels

Since long, gels are being used in the lubrication industry and cosmetic formulations. Gel fuels in which chemicals like ethanol are entrapped by a gelator are also being now used as domestic fuels. These fuels are easy to handle and safe to use. Gels are also being used for the delivery of pheromones in agricultural fields. Oil spillages can be overcome by using the organogelators which can absorb oils.

Applications of Metallogels

Other than the above mentioned applications, metallogels possess several advantages because of the presence of metal ions. They can have a broader spectrum when it comes to applications.

Metallogels provide a diversity of architectures such as rods, ribbons, tapes, tubes, helices etc. in nanometric dimensions. The superstructures formed by a given gelator molecule define a unique morphology, which can be used as templates for crystallization or for the synthesis of nanoparticles. Incorporation of metal ion into LMWGs and coordination directed gels display novel properties useful in adsorption, catalysis and as template for porous materials[7]which might find application in gas storage. As many supramolecular hydrogels are derived from naturally occurring molecules, they are expected to be biocompatible. As a result, they are being widely explored as media for tissue engineering,[8] owing to their structural similarity to the macromolecular components in the body. Gels are promising media for applications involving controlled release of molecules, specifically for drug delivery.[9]

Supramolecular gels may replace liquids in many of the technological applications in the not-so-distant future!

How to synthesize or design LMWGs?

The last 15 years have seen an ever increasing interest in low-molecular-weight gelators (LMWG). It is now beginning to be possible to move from the discovery of gelators by chance to attempting a more rational design of molecules for specific gel applications. Supramolecular assemblies formed by LMWGs are held together by non-covalent interactions. Thus, the primary condition for the molecules or complexes to behave as gelator is that it should have non-covalent interactions like H-bonding, π-π stacking, coordinate covalent bonds etc.Gelator should be soluble in the solvent which it incorporates to form a gel. Molecule or complexes forming a 1 D assembly have more chances of behaving as a gelator and form a gel.If the assembly extends in 2 or 3 dimensions than the molecular weight will increase and there are chances that it will either crystallize or precipitate instead of forming a gel.

Gels of a low molecular mass compound are usually prepared by heating the gelator in an appropriate solvent and cooling the resulting isotropic supersaturated solution to room temperature. When the hot solution is cooled, the molecules start to condense and three situations are possible:

1. A highly ordered aggregation giving rise to crystals i.e., crystallization
2. A random aggregation resulting in an amorphous precipitate
3. **An aggregation process intermediate between these two, yielding a gel**

Tuning the gel properties by variation in the structure of gelator molecules is a challenge and the present work is an attempt to explore in this area.

Scope of the present work

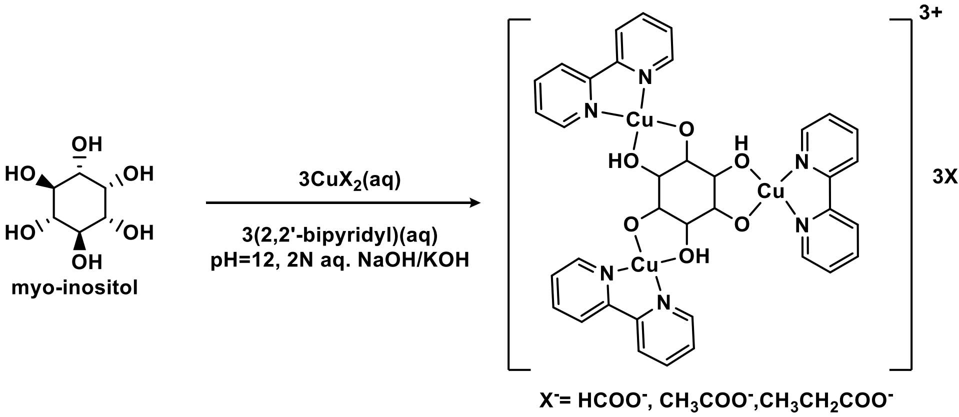
The present work includes preparation of trinuclear complex metallogelators[10] mainly derived from copper(II), myo-inositol and bidentate aromatic N-heterocycles, namely, 2,2;-bipyridine, 1,10-phenanthroline, 2,9-dimethyl-1,10-phenanthroline and 3,4,7,8-tetramethyl-1,10-phenanthroline. The gel formation in presence of various bases and anions has been examined. Systematic variation in the anions, and capping ligands has been made to tune the gel properties. The thermal, spectroscopic and microscopic properties of the resulting metallogels has been studied. Solvent uptake and applications such as catalysts for oxidation of phenols, biological applications, i.e. DNA and BSA binding, SOD mimic activity and antimicrobial acivity have been explored.

Chapter 1 will cover a detailed introduction to gels, metallogelators, the properties of metallogels and the probable applications. Work related to the present work and reported so far will be discussed. A detailed literature survey on metallogels will be presented.

Chapter 2

Design, synthesis and birefringent properties of hydrogels derived from complex metallogelator containing copper(II), 2,2'-bipyridine and myo-inositol

This chapter describes the synthesis of metallogels resulting from trinuclear copper(II) complexes. The trinuclear copper(II) complex, $[Cu_3(ins)(bipy)_3]X_3$, was prepared using myo-inositol(ins) and 2,2'-bipyridine(bipy) as ligands, in which X has been varied as $HCOO^-$, CH_3COO^- and $CH_3CH_2COO^-$. The complexes form metallo-hydrogels at elevated pH in presence of NaOH / KOH. The six gels formed have different combinations of carboxylate anions and sodium or potassium ions. The gel properties including T_{gel} are found to have significant dependence on the carboxylate anions used as well as the alkali.



Scheme 2.1: Scheme showing the synhesis of metallogelator complex.

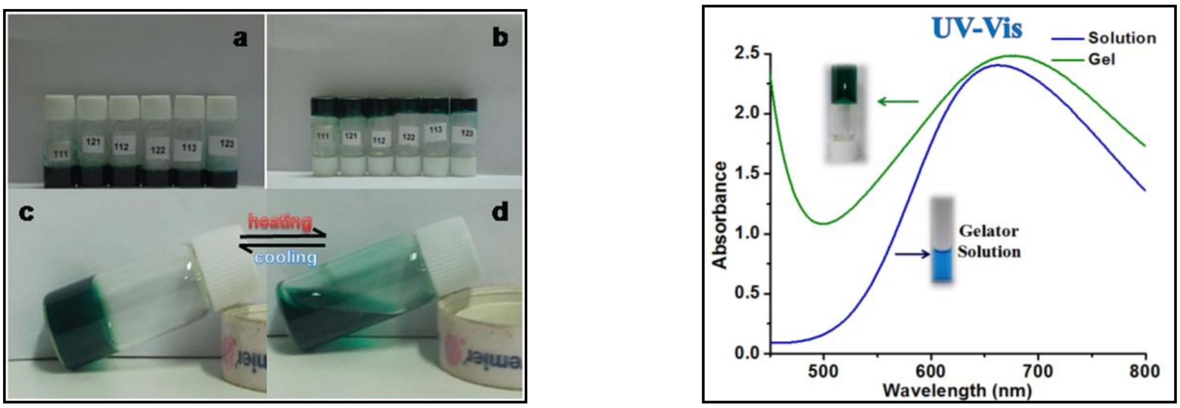


Figure 2.1: (Left)[a] Gels formed by the trinuclear Cu(II) complexes with myo-inositol, [b] Inverted images of vials which proves gel formation, [c]-gel and [d]-solution shows the sol-gel transformation on thermal stimuli.

Figure 2.1(Right) shows UV-Vis spectrum of the gel forming complex and metallogel-122

The structure of the metallogelator complex shown in scheme 2.1 has been optimized using DFT to support the proposed structure.

The metallogels have been characterized by thermal analysis and spectroscopic methods. Morphological properties have been studied using Polarizing Optical Microscopy (POM) and SEM in which the fibrous network resulting in the formation of metallogels could be captured. The metallogels are found to be highly birefringent and organize into quaternary structures which display unique patterns in the microscopic studies under polarized light.

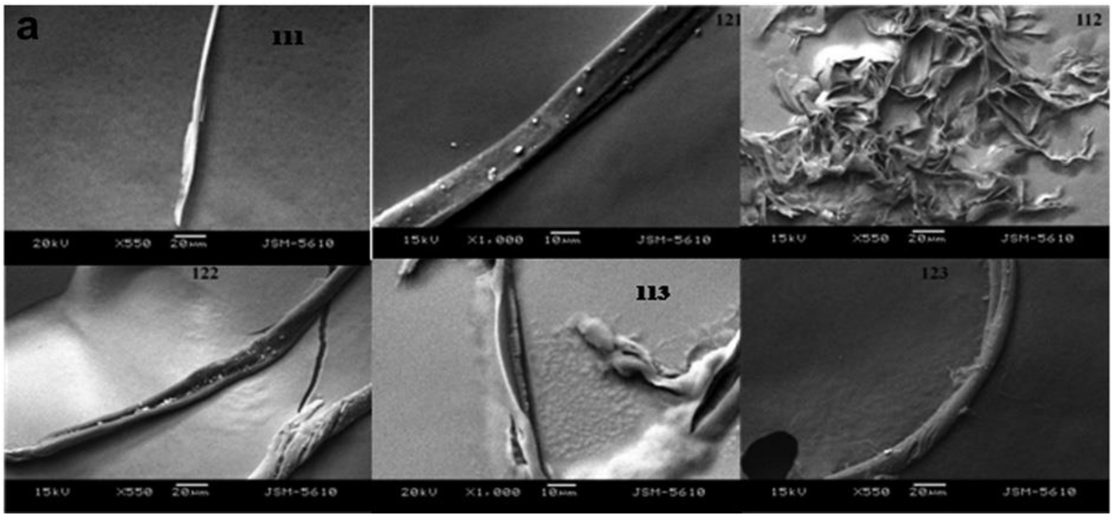


Figure 2.2: SEM images showing the fibrous assemblies observed in the metallogels.

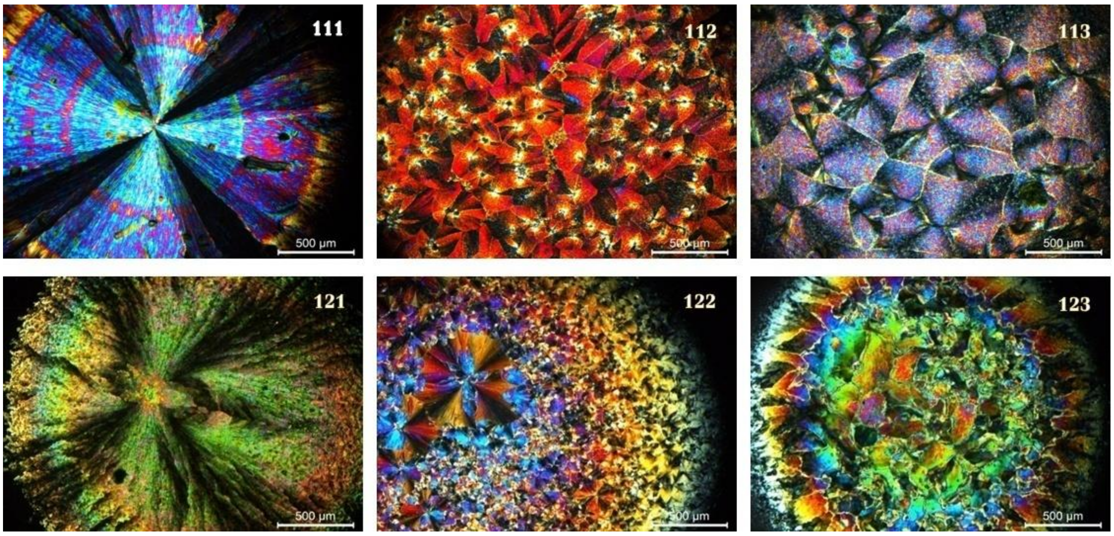


Figure 2.3: Polarized optical microscopy (POM) showing the birefringent property of metallogels.

From the POM images it is observed that the metallogels exhibit phases similar to lyotropic liquid crystals, which are temperature independent but dependent on solvent content. The birefringent images are observed when the metallogel loses water and is converted into xerogel. The behaviour is reversible and the birefringent pattern is lost once the xerogel absorbs moisture again. Thus,the images obtained can be considered similar to lyotropic liquid crystal systems exhibiting columnar assemblies. The gel forming complex, being trinuclear, has to be dissymmetric having at the most a C_3 symmetry axis, this can induce chirality in the molecule and is responsible for the birefringence property.

The SEM of the xerogels show the formation of compact fibrous structures, wherein each fiber is actually made up of intertwining thinner fibrils, the thickness of the fibers varies between 8 μm and 20 μm and the length is greater than 400 μm.

In order to find the mechanical strain/stress that a gel can undergo, rheology of the gels has been studied which indicated clear sol-gel transitions and the gel type.

Chapter 3

Investigating the effect of counter anions, terminal ligands and pH on gel formation and their use in designing metallogels

From the studies conducted in the previous chapter, it is observed that the gel properties depend on the alkyl carboxylates and the nature of the alkali used.Hence, it was thought of interest to examine the effect of presence of various anions and further variation in the nature of alkali.The effect of following anions has been examined:

$F^-,Br^-,I^-,Cl^-,SO_3^{2-},S_2O_8^-,NO_2^-,NO_3^-,SO_4^{2-},BrO_3^-,HPO_4^{2-},Cr_2O_7^{2-},CrO_4^{2-},HPO_4^-,CO_3^{2-},HCO_3^-$

The concentration of anions has been varied to have metal: anion ratio from 1:2 to 1:0.035.

Variation has been made in the alkyl carboxylates namely from formate to valerate.Apart from this dicarboxylate copper salts like copper oxalate, copper malonate and copper adipate were varied too. Other Copper like metal ions, viz. divalent Mn,Ni,Co and Zn also have been tried.

Efforts to prepare gels by using various simple metal salts like copper chloride, copper nitrate etc. were not successful.The presence of various alkyl carboxylates were found to be essential for gel formation. Hence, the ability of the gels to accommodate various anions has been examined by mixing a solution of $[Cu_3(bipy)_3(ins)](CH_3COO)_3$ with solutions of sodium/potassium salts of various anions in the required ratio, followed by maintaining the conditions for gel formation using NaOH.

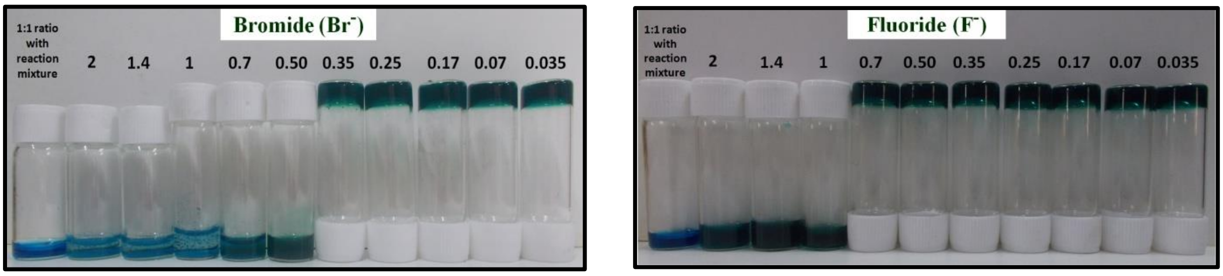


Figure 3.1: Representative figure showing the anion uptake capacity.

Table 3.1: Table showing the Anion uptake capacity of metallogels at different concentrations

Sr No.	Name of Anion	1:1 ratio of anion:Cu	2	1.4	1	0.7	0.50	0.35	0.25	0.017	0.07	0.035
1	Fluoride					G	G	G	G	G	G	G
2	Chloride				G	G	G	G	G	G	G	G
3	Bromide							G	G	G	G	G
4	Iodide										G	G
5	Bromate											G
6	Sulphate			G	G	G	G	G	G	G	G	G
7	Nitrate									G	G	G
8	Nitrite							G	G	G	G	G
9	Chromate										G	G
10	Dichromate											
11	Sulphite	G	G	G	G	G	G	G	G	G	G	G
12	NCS^-						G	G	G	G	G	G
13	$S_2O_8^-$									G	G	G

14	**HPO_4^-**							**G**	**G**	**G**	**G**	**G**
15	**CO_3^{2-}**	**G**				**G**	**G**	**G**	**G**	**G**	**G**	**G**
16	**HCO_3^-**		**G**			**G**	**G**	**G**	**G**	**G**	**G**	**G**

(*The ratio presents anion: Cu present in the metallogel,G represents gel)

A significant observation was made that the gel formation takes place when potassium carbonate or potassium bicarbonate was added to the gel forming solution in the bicarbonate:Cu(II) ratio of 1:1 and 2:1, respectively. The gel formation in these cases proceeds even in absence of caustic alkali. Thus, carbonate and bicarbonate anions were found to be helping in gel formation.

In order to find and verify the role of counter anions in the gel formation different copper salts were used as starting material. When copper nitrate, copper bromide, copper perchlorate and copper chloride were used as starting compounds, gel formation does not take place. While copper sulphate, copper alkyl carboxylates and copper alkyl dicarboxylates allow the formation of gels.

Alkyl carboxylates ranging from formate to valerate resulted in the formation of gels. Presence of alkyl chain beyond 5 carbon atoms in the alkyl carboxylates leads to a decrease in solubility and precipitation instead of gel formation.

In the case of dicarboxylates, copper oxalte and malonate resulted in the formation of gels.Because of the poor solubility of copper adipate, gel formation could not take place in it.

The gel formation was also tried using different ratios of copper chloride and copper sulphate along with copper acetate. The results have been tabulated and presented in Table 3.2 and Table 3.3.

Table 3.2. Effect of different ratios of copper acetate and copper chloride as staring materials on metallogel formation.

Sr No.	Copper Chloride(%)	Copper Acetate(%)	Result/Observation
1	0	100	Gel
2	25	75	Gel + solid
3	50	50	Gel + solid
4	75	25	Loose gel
5	100	0	Precipitation

Table 3.3. Effect of different ratios of copper sulphate and copper chloride as staring materials on gel formation.

Sr No.	Copper Sulphate(%)	Copper Acetate(%)	Result
1	0	100	Gel
2	25	75	Gel
3	50	50	Gel
4	75	25	Gel
5	100	0	Gel

In order to further study the various factors playing a role in the gel formation, different transition metal acetate salts, Ni, Mn, Co and Zn have been tried.

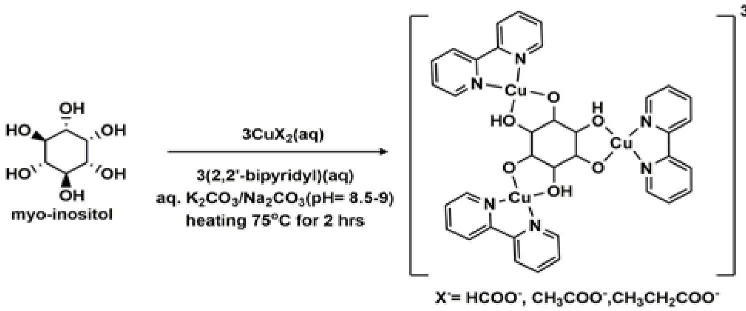
It was observed that only Ni acetate reulted in the formation of gels. However, these gels had less water retention capacity compared to Cu gels and were not reversible so they have not been explored further.

Chapter 4

Synthesis of metallogels of tricopper complex, $[Cu_3(bipy)_3(ins)]X_3$, with carbonate base and their application as heterogeneous catalysts for oxidation of phenols

As discussed in the chapter 2, the metallogels were formed by the trinuclear complexes in presence of caustic alkalis at pH 12. Even though the gels have myo-inositol(ins) and 2,2'-bipyridine(bipy) which are benign and non-toxic molecules, the highly alkaline pH restricts possibilities of any biological applications. As mentioned in the previous chapter it was observed that carbonate and bicarbonate bases can be used for gel formation instead of caustic alkali as bases. Hence, it was thought to explore these further. The reaction conditions were optimized and metallogels were formed in presence of carbonate bases.

Supramolecular metallogels resulting from an assembly of the trinuclear copper(II) complex of myo-inositol(ins) and 2,2'-bipyridine(bipy), $[Cu_3(ins)(bipy)_3]X_3$, where $X = HCOO^-$, CH_3COO^- *and* $CH_3CH_2COO^-$ in presence of carbonate bases have been explored. In these cases, the metallogels form at pH of 8.5-9, which is significantly lower as compared to the gels which have been reported in the previous chapters.



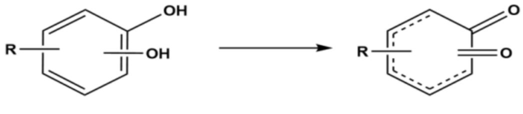
Scheme 4.1: The formation of trinuclear complex which results in the formation of metallogel in presence of alkali carbonates.

The metallogels thus formed have been characterized by UV-Vis, FT-IR and ESI-MS techniques. The morphology of the gels has been studied by SEM which indicates the presence of fibrous assemblies. POM images indicate the birefringent properties of the metallogels.

The metallogels formed were reversible with respect to the thermal stimuli. The T_{gel} values for all the gels have been determined. It was observed that the T_{gel}value decreases with the increase in alkyl chain length and increase in the positive charge density over the alkyl cation.

Oxidation of phenols using metallogels as catalysts:

These metallogels that have copper(II) which is a redox active metal ion and owing to its low redox potentials, it is a natural choice at the active site of most redox enzymes. Hence, it was thought of interest to study their ability as redox catalysts.These metallogels have been used as heterogeneous oxidation catalysts and the redox activity has beenexamined using different substrates like (i) 3,5-di-tert-butylcatechol (3,5-DTBC), (ii) 4-methyl catechol, (iii) 2,3-dihydroxy naphthalene, (iv) hydroquinone, (v) resorcinol and (vi) pyrocatechol



Scheme 4.2: General Scheme showing the oxidation of substrates

Oxidation of 4-methyl catechol using metallogel

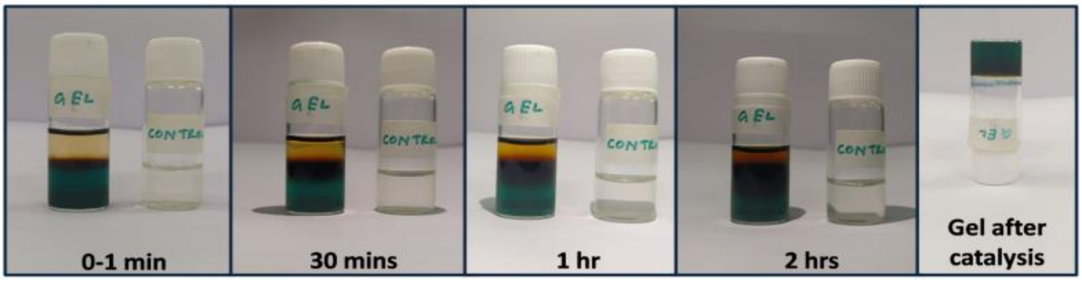


Figure 4.1: Figure showing the visual change in the colour of solution which is an indication of the oxidation of the substrate.

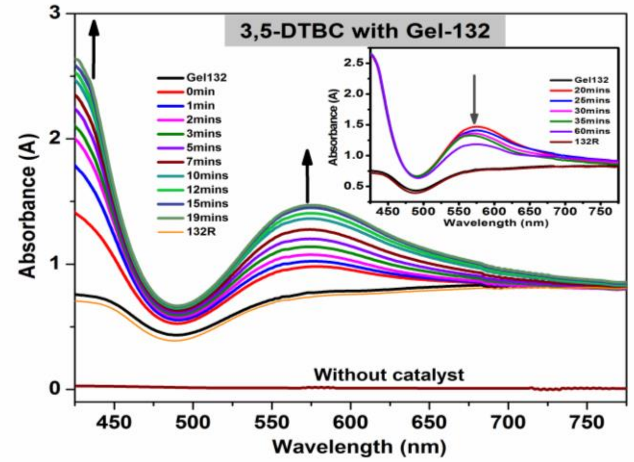


Figure 4.2: The UV-Vis absorption spectrum indicating the oxidation of 4-methyl catechol.

UV-visible spectroscopy was used to monitor the oxidation of 4-methyl catechol to 4-methyl quinone by the appearance of an absorption peak at 412 nm. As seen in **Figure 4.2,** it is observed that the intensity of peak at 412 nm increases with time. This is the first ever report of oxidation of 4-methyl catechol using a metallogel as a heterogeneous catalytic system. As the metallogel contains copper(II), the oxidation happens at the surface of the metallogel. As the product is soluble is methanol, the product can be easily recovered just by decanting the methanol solution leaving the metallogel intact.

Regeneration of metallogel after catalysis:
To ascertain that the chemical structure and the morphology of the metallogel remains unaltered before and after the oxidation of substrates, the UV-Vis spectra, ESR, SEM and FT-IR were recorded before and after the catalysis process. The UV-Vis spectra and FTIR of the metallogel after catalysis remains exactly the same indicating no change in the chemical composition of the metallogel. The morphology of the metallogel sample remained intact which was proved by SEM analysis. ESR spectra of the metallogel before and after the reaction show that the copper(II) in the metallogel is regenerated after the oxidation process. The ESR is a typical 4 line ESR spectra which is characteristic of a copper(II) complex.

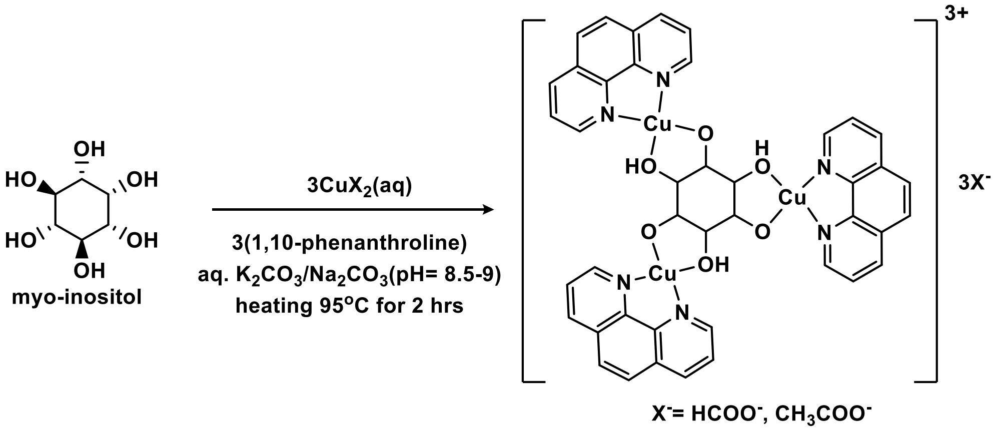
The ease of separation of the product, post reaction, faster oxidation processes and regeneration of metallogels make these gels excellent heterogeneous catalysts for such oxidation processes.

Chapter 5

Effect of capping agents on gel formation and uptake of organic solvents by metallogels derived from 1,10- phenanthroline containing tricopper (II) complex

In continuation of the systematic variation in anions and cations, as discussed in the earlier chapters, in order to further tune the gel properties it was thought to vary the bidentate capping ligands. 2,2'-bipyridine has been replaced by 1,10-phenanthroline and its derivatives.

The reaction conditions and volume of the solvent have been optimized, the metallogels were synthesized using 1,10-phenanthroline, neocuproine (2,9-dimethyl-1,10-phenanthroline) and 3,4,7,8-tetramethyl-1,10-phenanthroline as capping ligands in place of 2,2'-bipyridine.The used of 5-Nitro-1,10-phenanthroline did not result in gel formation. This can be mainly attributed to high electrostatic interactions that the nitro group possesses, which can result in very strong electrostatic interaction and precipitation of the complex instead of gel formation. Caustic alkalis as well as carbonate bases were used to make the pH alkaline which is required for the coordination of myo-inositol.



Scheme 5.1: Synthesis of metallogelator complex using 1,10-phenanthroline as a capping agent.

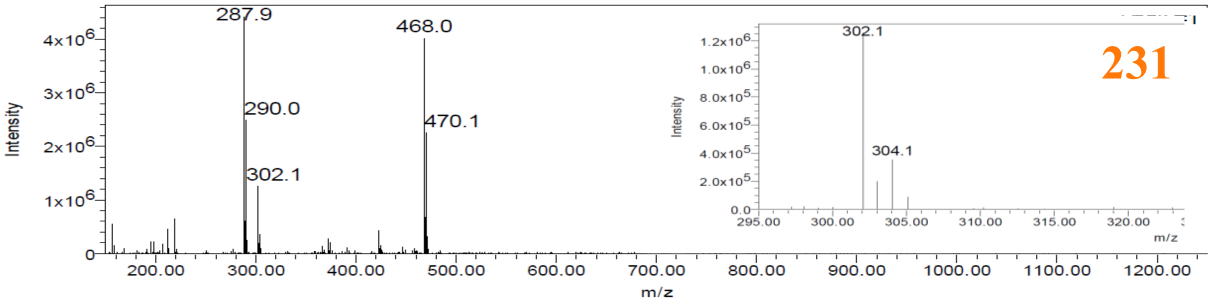


Figure: 5.1: ESI-MS of the metallogelator complex [Cu$_3$(phen)$_3$(ins)](HCOO)$_3$ formed using potassium carbonate as base.

The gels have been further characterized by various techniques. The SEM analysis has shown the formation of fibrous assembly.

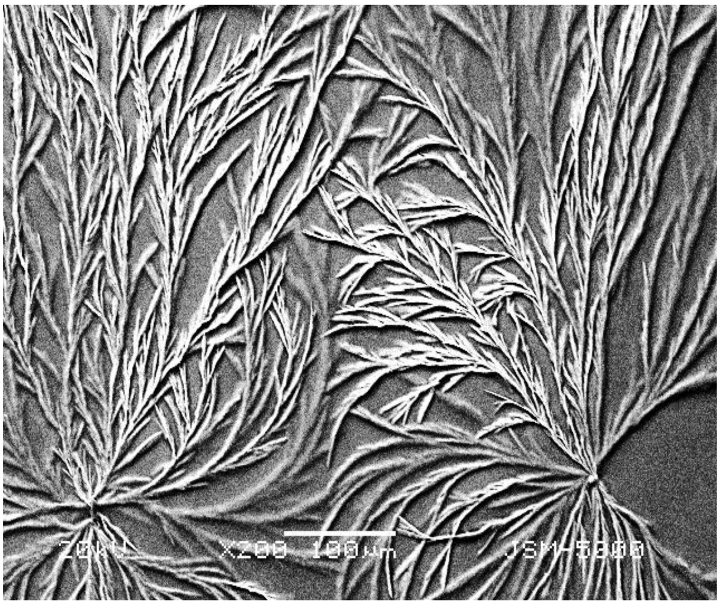


Figure 5.2: SEM analysis of the metallogel shows the presence of fibrous assembly.

Solvent uptake studies of metallogels:

Since the capping agent was changed from 2,2'-bipyridine to phenanthroline and its derivatives, the exterior hydrophilicity / hydrophobicity is expected to change and result in some interesting properties. It was thought of exploring the uptake of organic solvents by metallogels as phenanthroline has more hydrophobic character than 2,2'-bipyridine.The experiments were carried out to check the capacity of preformed metallo-hydrogels to incorporate another solvent. A striking observation was made that the gels once formed can encapsulate various organic solvents to varying extent. This has been explored in detail.

- The metallogels having phenanthroline as capping ligands and synthesized using carbonate bases are found to be compatible with a variety of organic solvents like methanol, ethanol, DMSO and DMF.
- The metallogels synthesized using caustic alkali were even more versatile than the carbonate gels and they could even uptake CH_3CN and THF in addition to other solvents mentioned above.
- Further, the T_{gel} properties were also dependent on the nature and the amount of solvent incorporated.
- The phenanthroline gels have a tremendous solvent uptake capacity, especially methanol. They can absorb 20 times the volume of methanol(0.63 wt%) of their original volume at room temperature. This is very unusual for metallogels and can lead to various applications.

Chapter 6

DNA & BSA binding, superoxide dismutation, antimicrobial activity and cytotoxicity of copper(II) containing metallogelator complexes

The redox-active transition metal ions can be best utilized in catalyzing the dismutation of superoxide anion, which is a product of oxygen metabolism in the living systems. Naturally occurring superoxide dismutases in living systems contain Cu/Zn and Mn centers, which act as a natural defense mechanism against the superoxide-mediated oxidative damages in the cells.

The catalytic cycle of a conventional SOD follows a ‘ping-pong’ mechanism, where disproportionation of two superoxide anions ($O_2^{\bullet -}$) forms molecular oxygen (O_2) and hydrogen peroxide (H_2O_2). Synthetic enzymes (synzymes) which can mimic a natural enzyme function carry a potential to act as pharmaceutical agents for treatment of various neuro degenerative disorders and may possess superior anticancer activity.

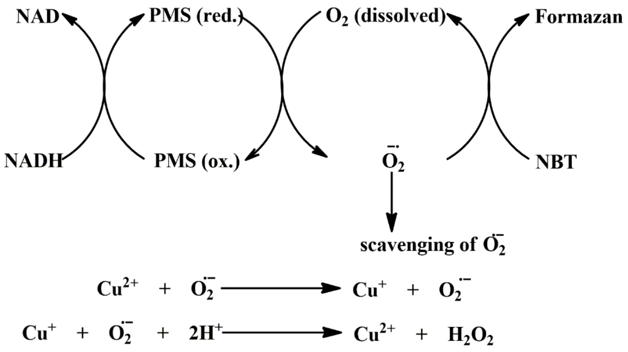


Figure 6.1 Ping-pong mechanism of dismutation of superoxide ions

The antioxidant SOD activity (Figure 6.1) of the trinuclear complexes responsible for metallogel formation have been investigated *in vitro* by NBT assay in a phosphate buffer with pH= 7.8 using PMS as the source of superoxide ions. The superoxide ions generated by PMS drive the reduction of NBT to formazan, a bluish black colored complex, whose absorption can be observed at 560 nm using UV-vis spectroscopy. The activity is measured in terms of IC_{50} value, which corresponds to the concentration of complex which decreases the rate of NBT reduction by 50%.

Complex	**IC_{50} (μM)**
131	**2.9**
132	**0.8**
133	**0.56**
151	**1.02**
152	**0.45**
153	**0.37**
Native Cu-Zn SOD	0.04
Ascorbic acid/Vitamin C	852
$Cu(en)_2Cl$	1000
$CuCl_2.2H_2O$	0.910
Cu (II) salen complexes	0.75-3

Table 6.1 IC_{50} values of synthesized complexes and some known SOD mimics

It is remarkable to note that the IC$_{50}$ values for the complexes fell in the range of 0.37-2.9 µM, in the order, 153 > 152 > 133 > 132>151>131

We can infer that the synthesized complexes are more efficient than Vitamin C, $CuCl_2$, $Cu(en)_2$ and many of the previously reported SOD mimics.

BSA Binding studies with metallogelator complexes:

The fluorescence of BSA is caused due to the presence of tryptophan (Trp) and tyrosine (Tyr) residues in its structure. A quenching in the fluorescence intensity of BSA (along with a blue shift) upon addition of any compound is associated with conformational and dynamic changes in the protein structure.

During the BSA binding studies with complexes it was observed that the intensity decreases with increasing concentrations of all complexes. The values of quenching constants for the binding of BSA to the compounds are of the order 10^{13} $Lmol^{-1}s^{-1}$.

The double logarithmic Scatchard plots for all metallogels in BSA studies are found to be straight lines, which suggests that the quenching is caused by the formation of a complex, indicating a static quenching mechanism. The *n* value in all complexes are close to 1, indicating the presence of single binding site in the BSA protein structure.

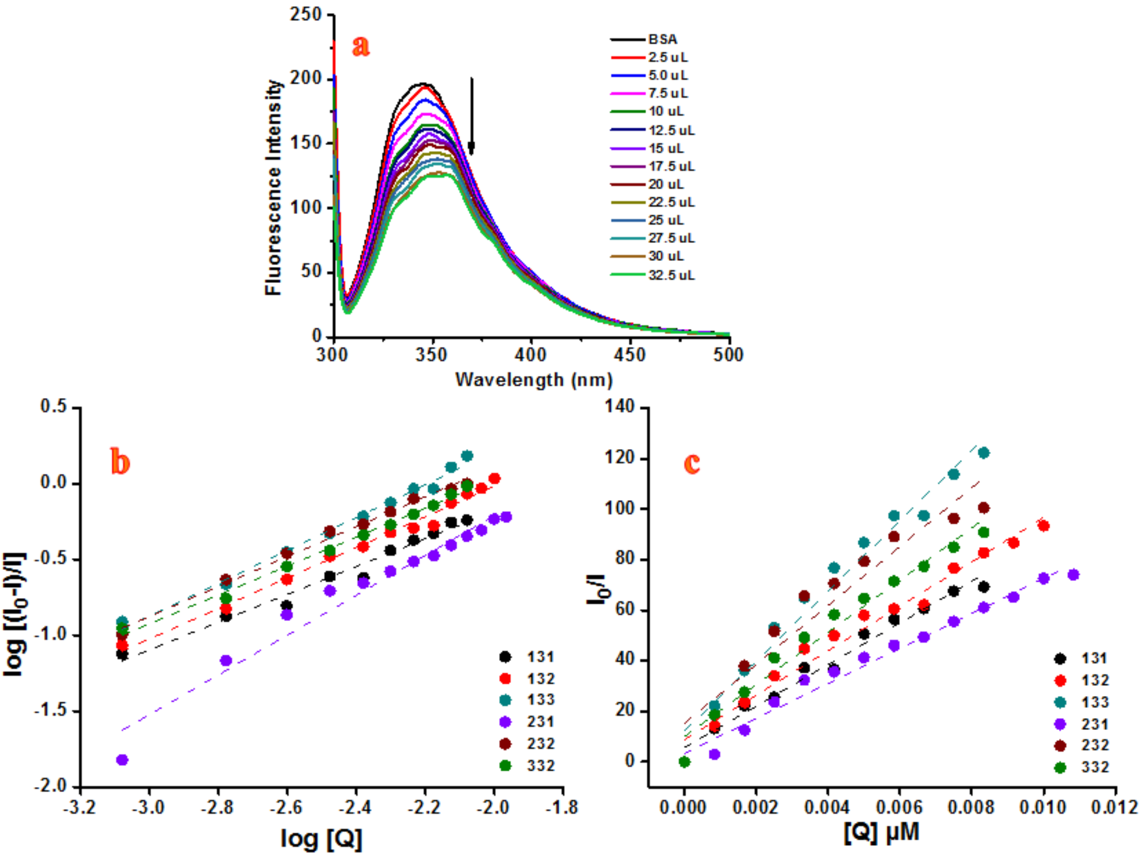


Figure 6.2 (a) The emission spectra of BSA (1 x 10^{-6} M; λ_{ex} = 296 nm, λ_{em} = 344 nm) in presence of increasing amounts of metallogelator complex solutions (b) Scatchard plots and (c) Stern-Volmer plots of fluorescence quenching with different concentrations of metallogel solutions

DNA Binding Studies with metallogelator complexes:

From the UV-vis spectra, it was observed that the absorption band around 300 nm caused by π-π* transition suffers significant hypochromism in all metallogels. As the complex concentration in the cuvette increases the absorption intensity decreases which is an indication of metallogelator complex binding[11] with DNA through intercalation mode.

The fluorescence spectral titrations using EB caused a quenching in the fluorescence intensity of DNA-EB complex on gradual addition of complexes.

From the UV plots it is found that the values for all the complexes fall in the magnitude of **$10^5/10^6$ M^{-1}**, which suggests that the complexes interact with DNA strongly. UV-Vis spectroscopy and fluorescence studies show that the gels having phenanthroline and neocuproine as capping ligands have good binding with DNA and BSA.

Anti-microbial Activity of metallogelator complexes:

Since the metallogelator complexes have all components are benign, they are expected to be highly biocompatible. Having the presence of copper(II), their anti-microbial activity has been examined. They have been found to be active against gram positive bacteria more as compared to the gram negative bacteria. The gels having phenanthroline and neocuproine as capping agents also show very good activity against grampositive bacteria and lower MIC against Staphylococcus aureus as compared to the standard Ciprofloxacin drug which can be further enhanced by absorbing a suitable drug in the gel.

Finally, the work will be summarized with a comparison of the gel properties and their activity with the constituents of metallogels.

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