A SYNOPSIS

of the thesis entitled

Synthesis, Characterization and Applications of Novel Self-Assembled Fibrillar Networks

to be submitted

as a partial fulfilment for the award of the degree of

DOCTOR OF PHILOSOPHY

in

CHEMISTRY

by

Patel Ajaykumar Manibhai

under the supervision of

Dr. Amar Ballabh, Associate Professor

Department of Chemistry
Faculty of Science
The Maharaja Sayajirao University of Baroda
Vadodara 390 002, Gujarat (INDIA)

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Research Student	: **Patel Ajaykumar Manibhai**
Title of Thesis	: **Synthesis, Characterization and Applications of Novel Self-Assembled Fibrillar Networks**
Supervisor:	: **Dr. Amar Ballabh** Associate Professor
Department	: **CHEMISTRY**
Faculty	: **SCIENCE**
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Patel Ajaykumar Manibhai
Research Student

Dr. Amar Ballabh
Research Supervisor

Prof. Ashutosh Bedekar
Offg. Head
Department of Chemistry

The thesis will be presented in the form of following chapters –

Chapter 1
Introduction

Chapter 2
A new series of thiazole-based gelators and its potential application

Chapter 3
Synthesis, Characterization and application of uriede based thiazole derivatives

Chapter 4
Design, synthesis and characterization of benzimidazole based amide and urea derivatives as Supramolecular gelators

Chapter-1
Introduction

Supramolecular Chemistry

Supramolecule is “chemistry beyond a molecule” as defined by Dr. Jean Marie Lehn providing a platform to study non-covalent and weak interactions of systems or the chemistry of system where molecules are able to organize and assemble themselves into complex entity. The non-covalent interactions which supramolecules focuses on includes forces of hydrogen bonds, electrostatic bonds, π-π bonds, hydrophobic forces, metallic interactions, and weak Van der waals bonds. In recent years, supramolecular chemistry is recognized as one of the most active fields of science, mainly due to its dynamic nature, academic interest and real-life applications. The recent progress in supramolecular chemistry however, elongated from molecular recognition to exploring novel applications in gas/solvent storage, smart materials, molecular switches etc.

Gels

Gel is a solid-like material mainly composed of liquid phase (solvents) and small concentration of solid phase (gelator). The solid-like appearance of the gel can be attributed to the immobilization of the solvent molecules in the three-dimensional (3D) network formed by the gelator molecules.

Low molecular Organo-gelators (LMOGs)

Amongst the areas of supramolecular chemistry, **low molecular-weight organogelators (LMOGs)** have been considered to be one of the most interesting soft and smart materials due to their ability to construct polymeric structures from small molecules through non-covalent interactions. LMOGs are small molecules (molar mass < **3000**) which self-assemble in the given solvent to form gel. Gelators capable of hardening organic solvents are popularly known as organogelators; While, gelator which shows gelation behaviour for aqueous solvent, are called hydrogelator. The gelators which are capable of hardening both organic solvents as well as water are termed as ambidextrous gelators.

The key to the gel formation is the self-assembly of the LMOGs, driven by non-covalent interactions (such as **hydrogen bonding, π-π interactions, metal–ligand coordination, van der Waals forces, etc.** to form entangled **Self-assembled Fibrillar Networks (SAFINs).** Dynamic nature of these networks makes LMOGs respond to the external stimuli such as temperature, lights, solvent, pH and redox systems.

How are they prepared?

They are prepared by heating the gelator (LMOGs) in an appropriate solvent which results in isotropic supersaturated solution. When this hot solution is cooled, the molecules start to assemble and three situations are possible (Figure 1). These are:

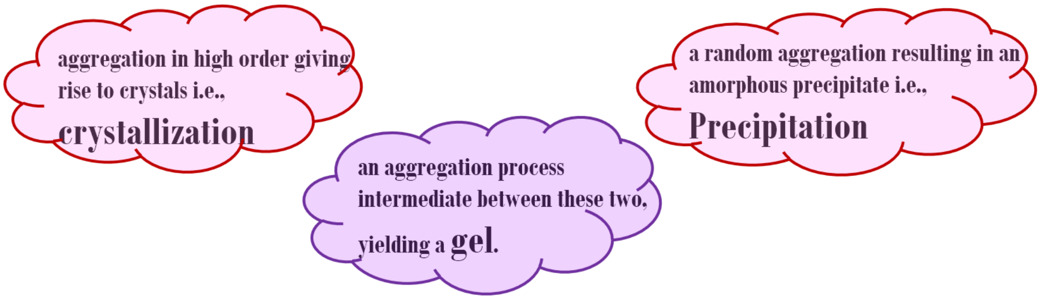


Figure 1: Possible ways of condensation of molecules in a solution

Mechanism of Gelation

Every process of gelation involves, self-association of the gelator molecules to form long, polymer-like fibrous aggregates which get entangled during the aggregation process forming a matrix that traps the solvent mainly by surface tension and capillary forces. This process prevents the flow of solvent under gravity and the mass appears like a solid(gel) as depicted in Figure 2.

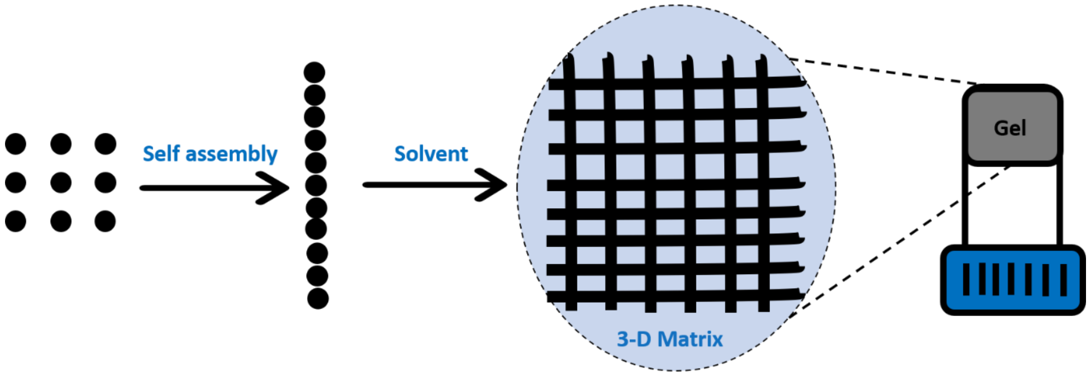


Figure 2: Cartoon representation for mechanism of gelation

The matrix form during the aggregation process may range from nano-meter to few micrometres. At microscopic level, this self-assembled network was probed using conventional imaging techniques such as scanning electron microscopy (SEM), Transmission electron microscopy (TEM), Atomic force microscopy (AFM), while thermal and mechanical properties were elucidated to understand the interactions between these structures. Techniques like X-ray diffractions (XRD) and small angle neutron and X-ray scatterings (SANS, SAXS) shed light on molecular level packing.

Despite of having wide applications, early development of LMOGs is serendipitous, rather than its design. Therefore, it is important to decipher the mechanism of formation of supramolecular gel and to explore the link between the molecular packing, supramolecular assembly of molecular fibers, and three-dimensional (3-D) macroscopic network leading to gelation behaviour.

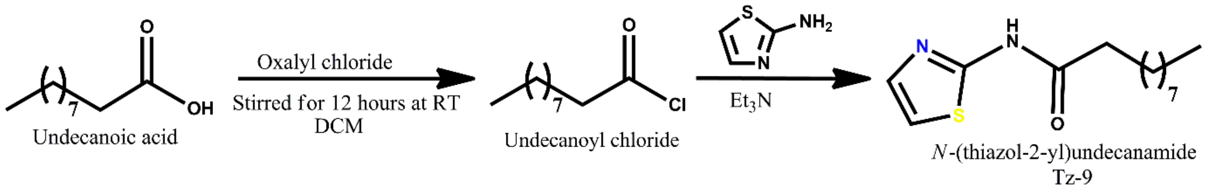
In order to meet all objectives, the contents of the present thesis are summarized into four chapters-

Chapter 1 will cover an introduction of supramolecular chemistry and physical gels. The role of various non-covalent interactions responsible for formation of supramolecular assemblies will be elaborated. Low molecular mass gelators (LMOGs), their design, classification, characterization and applications will also be discussed.

Chapter-2

A new series of thiazole-based gelators and its potential application

In the present work, we synthesized a new thiazole based aliphatic amides (Scheme 1) to understand the hierarchical assembly of molecules in the solid-state to metastable gel state.
We decided to direct our effort to establish the relationship between packing of **Tz-9**[N-(thiazol-2-yl)undecanamide] in solid-state (SANS, Powder and single crystal X-ray study) and supramolecular assembly in gel state (variable temperature SANS study). Moreover, **Tz-9** was also explored towards anion sensing application.



Scheme 1: Synthetic scheme for Tz-9

The compound **Tz-9** was examined for its gelation property and turned out to be an excellent gelator for polar solvent with low MGC (Minimum gelator concentration) for acetonitrile gel (2.78 (% w/v)). As evident from the PXRD patterns of xerogel, simulated and bulk solid most of the peaks match well, especially, in case of bulk and xerogel (obtained from ACN). PXRD of bulk solid of **Tz-9** revealed that d-values of four strongest peaks 17.4, 9.1, 6.0, and 4.5 Å, approximately follow ratio of 1:1, 2:1, 3:1 and 4:1, respectively, suggesting a layered structure. The preliminary SANS study of solid-state study of thiazole-based amide suggested a well-defined cylindrical assembly in solid-state. (Figure 3c)

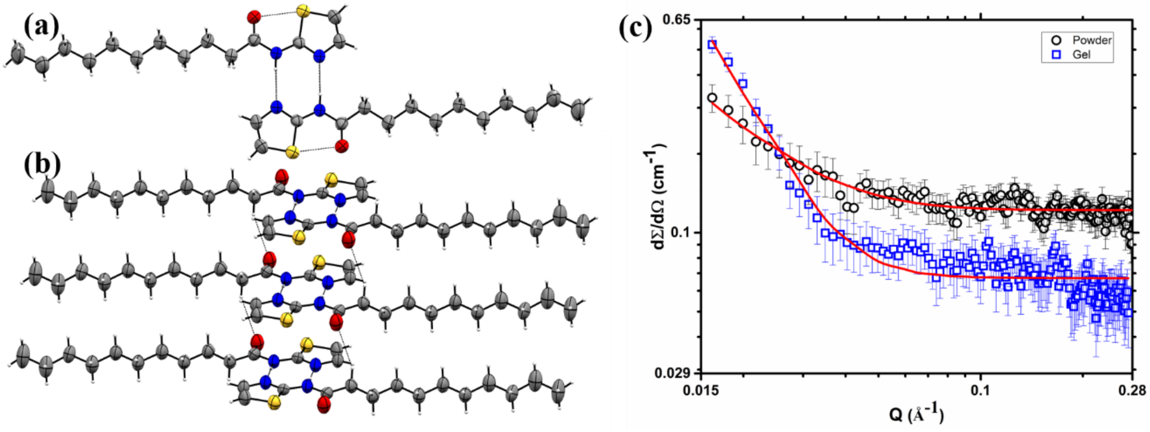


Figure 3 (a) Dimer motif form by two molecules of Tz-9, *(b) "Molecular staircase" formed by dimer of* Tz-9 *and (c) SANS profile of solid powder and acetonitrile gel of* Tz-9

Temperature dependent SANS study of **Tz-9** gel in acetonitrile suggested the three-dimensional network of gel primarily consisting of monodisperse cylindrical fibers with almost the double molecular diameter than the cylindrical fibers in the solid state. Moreover, the decrease in molecular diameter of cylindrical fibers in gel network with increase in temperature and complete collapse of cylindrical assembly at higher temperature (70 °C) was evident from temperature dependent SANS study (Figure 4a). Single crystal structure of **Tz-9** packing displayed dimeric zero-dimensional packing of the molecule with the extended aliphatic chain which was extended further to 2D network through weak noncovalent interactions such as C–H···O and van der Waals interaction (Figure 3a, 3b). A probable mechanism of packing of **Tz-9** molecules starting from solid-state to supramolecular assembly inside the gelator fiber is proposed based on various physical-chemical analysis. A potential application of **Tz-9** as fluoride ion sensing with good selectivity and sensitivity may open an avenue to develop as sensors (Figure 4b).

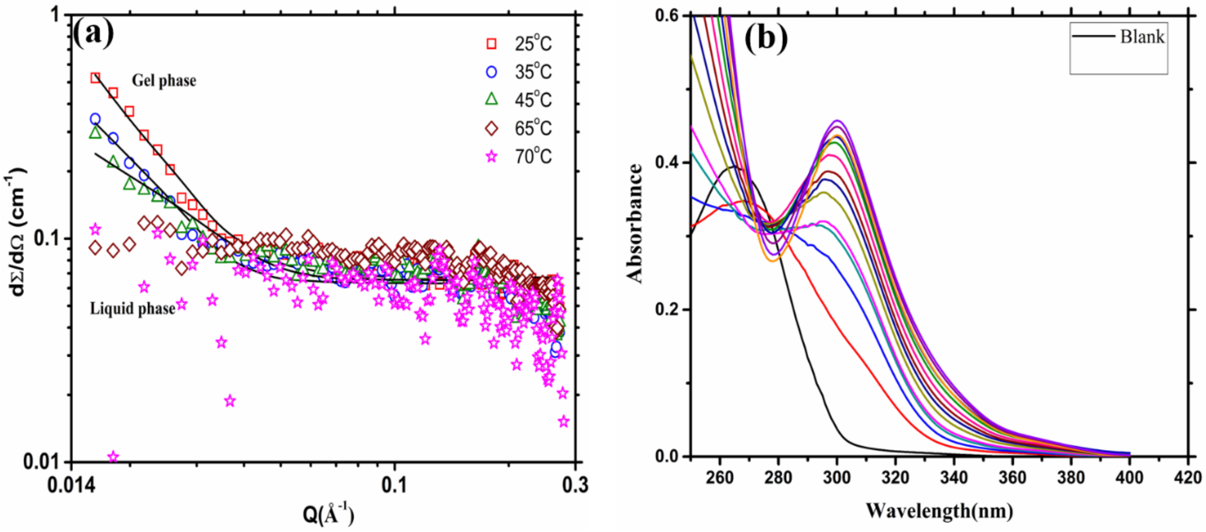
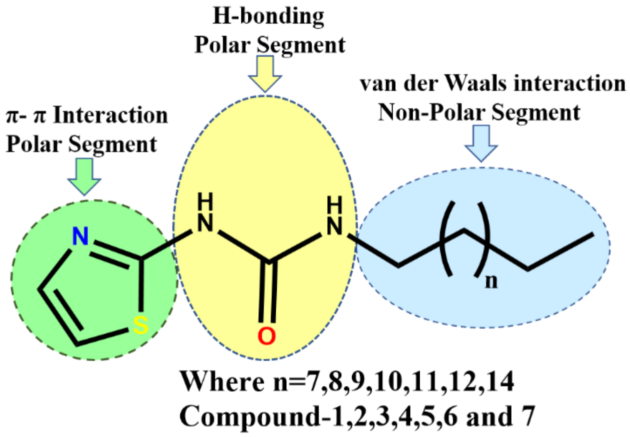


Figure 4: (a) Fitted SANS profile for compound Tz-9 at varying temperature (b)Change in absorption spectra of Tz-9 with the addition of TBAF (0-35 MM) in THF

Chapter-3

Synthesis, Characterization and application of uriede based thiazole derivatives

In this chapter, we synthesized a series of compounds having thiazole moiety, hydrogen bonding site (urea functional group), and long alkyl chain (**compounds 1–7**). The systematic increase in the aliphatic long chain from decyl to heptadecyl was carried out to explore the role of van der Waals interaction (or hydrophobic effect) on gelation process along with reliable 1D hydrogen bonding urea functional group. (**See Scheme 2**). All the synthesized compounds were investigated for their potential gelation behaviour towards polar/non-polar solvents and the mixture of solvents. To get an insight into the packing of molecules in solid-state, solution, and gel phases various physicochemical techniques were employed such as SANS, SEM, PXRD, DFT calculation etc. Moreover, the anion sensing capability of these compounds were investigated.



No. of methylene group	Name of compound
10	Compound-1
11	Compound-2
12	Compound-3
13	Compound-4
14	Compound-5
15	Compound-6
17	Compound-7

Scheme 2: List of organic compounds synthesized (compounds 1–7).

In this series, we successfully demonstrated the simple strategy of designing molecules with components containing heterocyclic ring (thiazole moiety), 1-D hydrogen bonding sites (urea functional group), and a long aliphatic chain for inducing van der Waals interactions. Even though none of the synthesized compounds turned out to be hydrogelator but all were found to be capable of gelling a mixture of solvents containing water. In Rheological measurements of gels (1–7) the storage modulus (G') is almost an order greater than G" (loss modulus) (except for compound 2) indicating the formation of a strong viscoelastic gel. FTIR spectra of all compounds prepared from different solvents were also recorded. Interestingly, almost superimposable spectra of xerogel and bulk solid suggest retention of hydrogen bonding pattern in both states. Most of the peaks in PXRD in bulk and xerogel showed a reasonable match in all the studied compounds (bulk and xerogel). SANS analysis of supramolecular assembly of compounds in solid-state suggested the formation of cylindrical assembly with a different molecular diameter strongly dependent upon the long aliphatic chain. The temperature variation SANS study on gel samples suggested a loose assembly of irregular fibers, which was further corroborated with SEM micrographs of xerogel (Figure 5).

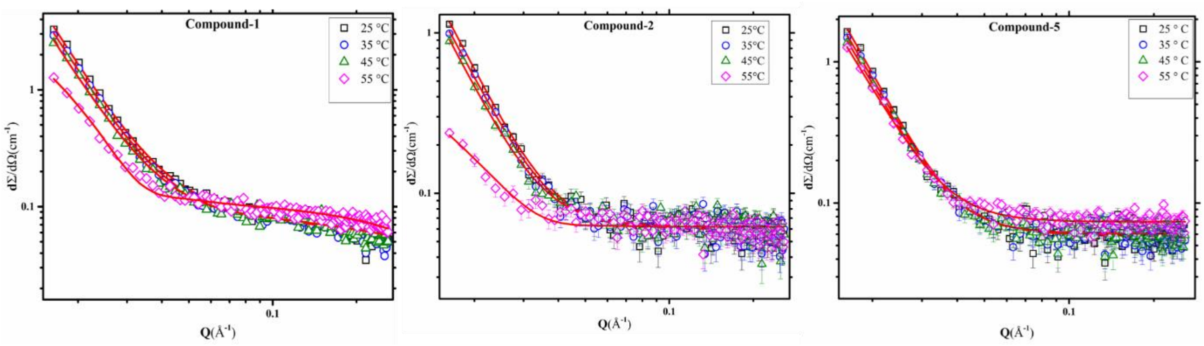


Figure 5: SANS profile of gelator 1, 2 and 5 at various temperature

Interestingly, the iodide ion sensing ion in the solution and gel phase instead of chloride/fluoride ions (commonly sensed by urea-based compounds) prompted us to conclude the syn-anti conformation of the urea functional group, which was further supported by DFT calculation and NMR titration. The degelation (gel-to-sol) transition with the addition of iodide salts promises an attractive method of selective identification and detecting iodide ions. To the best of our knowledge, the LMOGs with iodide sensing are rarely reported in the literature and the present study provides an opportunity to design new LMOGs with potential applications such as iodide ion sensing (Figure 6).

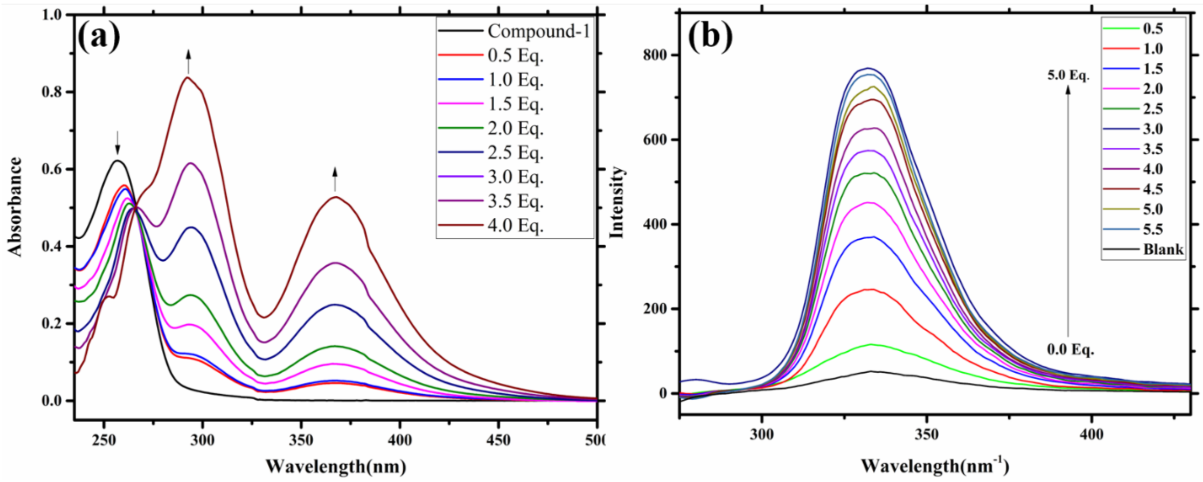


Figure 6 (a) Change in UV–Visible of compound-1(50 μM) with addition of tetrabutylammonium iodide in THF solvent (b) emission spectra of compound-1(50 μM) in THF with gradual increase in the tetrabutylammonium iodide concentration

Chapter-4

Design, synthesis and characterization of benzimidazole based amide and urea derivatives as Supramolecular gelators

Benzimidazole draw attention due to availability of N-H or polar C-H bonds for hydrogen bonding and charge-charge interaction with the ionic species. Also, the benzimidazole structures have π-stacking ability, which is advantageous during molecular aggregation. Benzimidazole derivatives are widely chosen as a multifunctional unit for the synthesis of bioactive organic compounds because of their structural similarities to the natural nucleotides. As from the report various imidazole derivatives has been found but no report of benzimidazole based LMOGs inspired us to synthesize amide and urea derivatives of benzimidazole and were probed for gelation in various solvents.

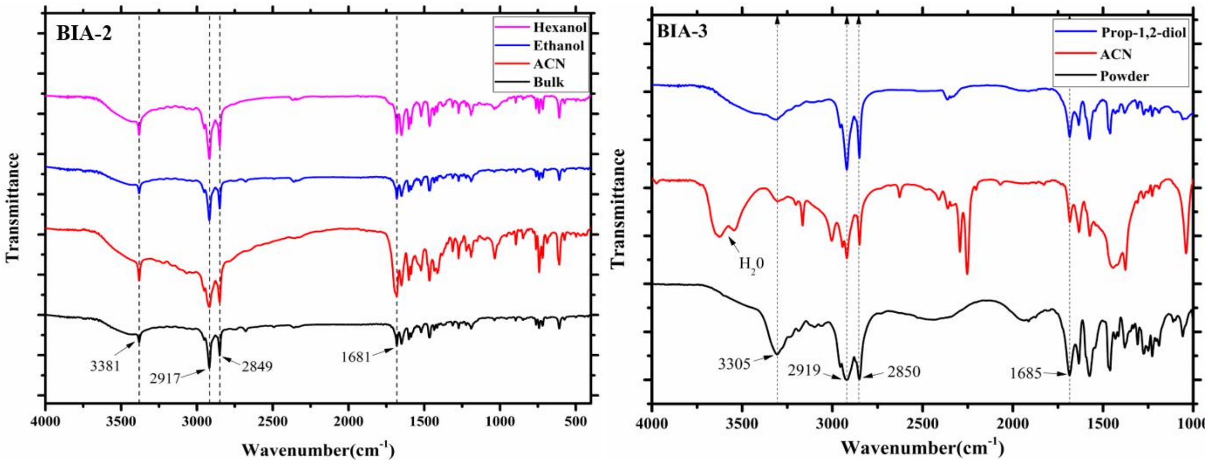


Figure 7: IR spectra of bulk and xerogel from various solvents

The reason for the insertion of amide between benzimidazole and alkyl chain is that as carbonyl oxygen of amide is hydrogen bond acceptor and presence of N-H hydrogen readily makes it donor which increase the intermolecular interaction. Furthermore, the selection of urea is due to its ability to construct directional assembly because of self-complementary hydrogen bonds between oxygen(C=O) and N-H hydrogens.

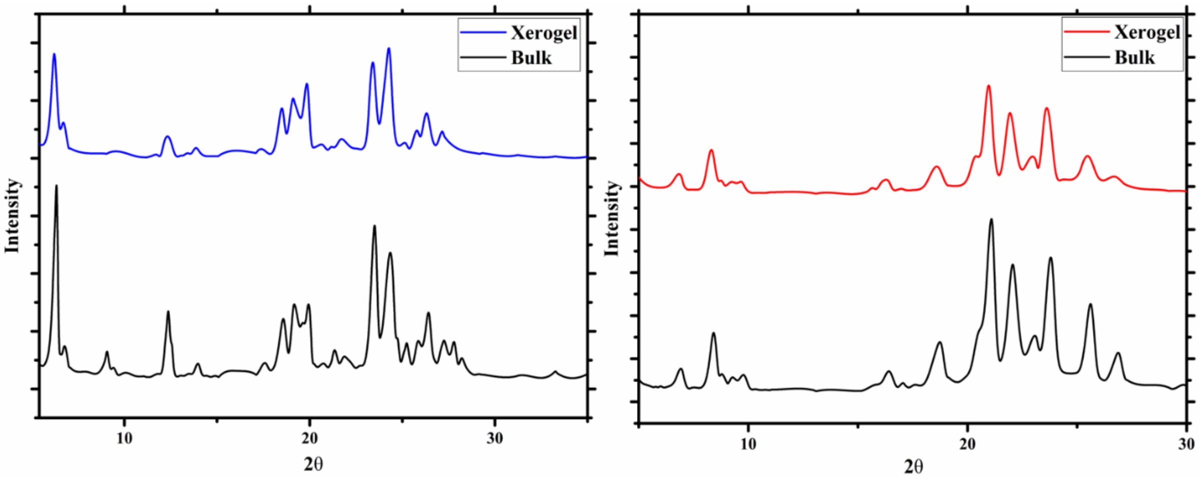


Figure 8: X-ray diffraction patterns of bulk and xerogel

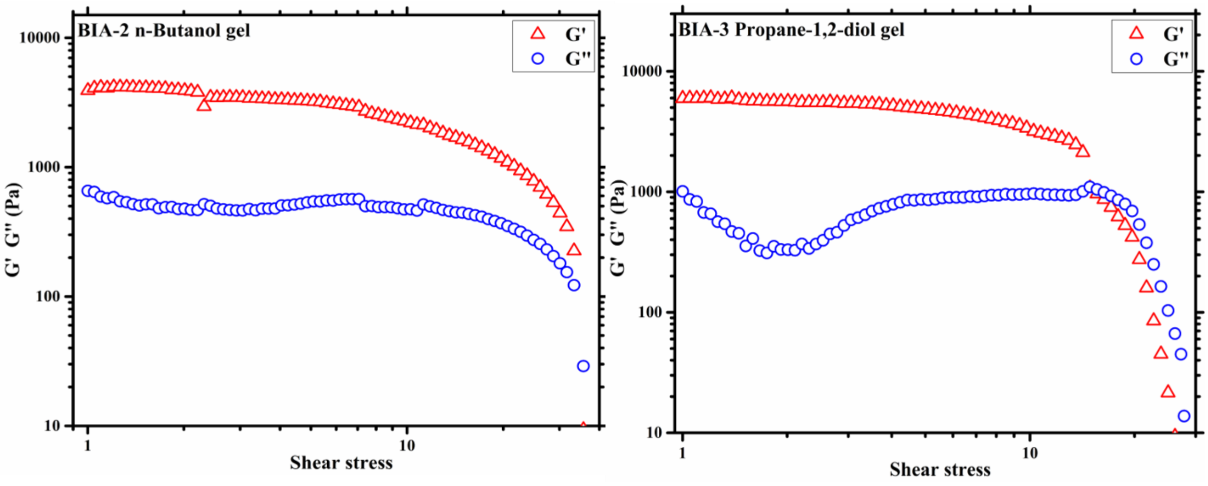


Figure 9: Evolution in G’ and G” with applied stress

All the compounds were characterized using various physico-chemical techniques like NMR, IR, SEM and Rheology. Furthermore, comparative PXRD and IR was also analyzed.

All the compound shows good gelation behavior in various polar and non-polar solvents. In Rheological measurements of gels, the storage modulus (G’) is almost an order greater than G” (loss modulus) indicating the formation of a strong viscoelastic gel (Figure 9). Primary gelation studies conclude that amides are better gelators than their urea analogues. FT-IR studies confirmed a similar packing in bulk and xerogel form (Figure 7). In PXRD patterns of xerogel and bulk solid, most of the peaks matches well (Figure 8). Overall, this data confirms that the chemical nature of the compound remained intact after gel formation. SANS will be carried out on all the gels, to explore the probable mechanism of gelation process. Comparative studies between amide and its urea analogues may open new avenue for designing LMOGs with the wide applications.

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Patel Ajaykumar Manibhai	**Dr. Amar Ballabh**
Research student	Research Supervisor