Chapter 1

INTRODUCTION

Published in

1. **Chapter 2. Multifunctional Supramolecular Gels – An Overview. in *Advances in Chemistry Research. Vol. 76* (Nova Science Publishers, USA, 2022).**
2. **Chapter 5. Low Molecular Mass Gelators Based on Thiazole Derivatives – Design and Function. in *Advances in Chemistry Research. Vol. 76* (Nova Science Publishers, USA, 2022).**
3. ***Recent Advances in Petrochemical Science*, 7 (2022) 3.**

1.1 SUPRAMOLECULAR CHEMISTRY

Supramolecular chemistry embodies the creative power of chemistry. By its very essence, by its ability to create and through the beauty of its objects, chemistry is an art as well as a science.

JEAN-MARIE LEHN, 1995[1]

Supramolecular chemistry is the branch of chemistry associated with the study of complex molecular systems formed from several discrete chemical components.[2] These entities arise from reversible intermolecular interactions in response to chemical or environmental stimuli. They are known to behave in unique ways and display novel properties. Jean-Marie Lehn defined supramolecular chemistry as – "*Just as there is a field of molecular chemistry based on the covalent bond, there is a field of supramolecular chemistry,* ***the chemistry of molecular assemblies and of the intermolecular bond***." He further refined his definition as "***the chemistry beyond the molecule bearing on the organized entities of higher complexity that result from the association of two or more chemical species held together by intermolecular forces***".

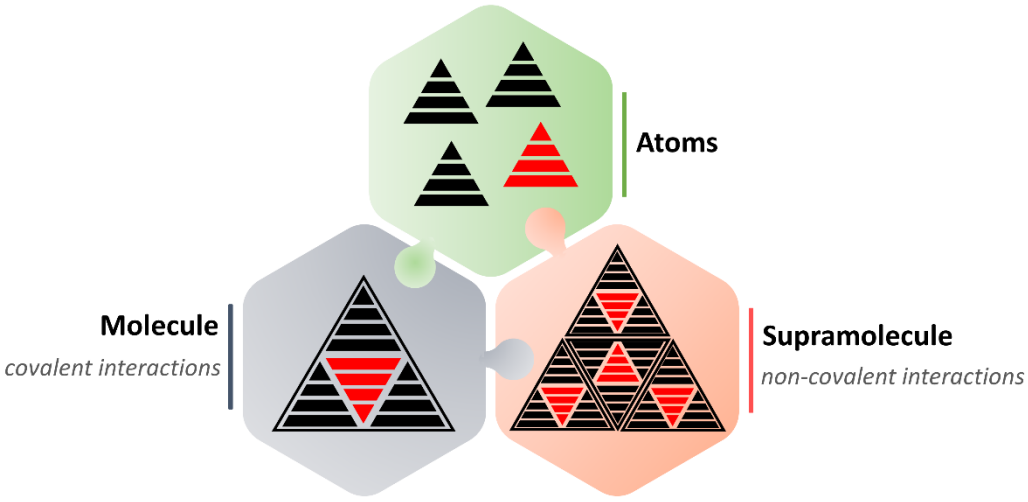


Figure 1.1 Representation of generation of supramolecules

This concept of supramolecular chemistry gained a wider scientific recognition following the award of the 1987 Nobel Prize in chemistry to Donald Cram, Jean-Marie Lehn and Charles Pedersen for their development and use of molecules with structure-specific interactions of high selectivity. Various levels of molecular complexities have

been identified since then, such as specific host-guest interactions, molecular assembly, self-assembled systems, to name a few. The role of non-covalent interactions in driving the formation of supramolecular systems was also highlighted (Figure 1.1). These include the hydrogen bond, van der Waals interactions, C-H…π, π…π stacking, charge transfer, electrostatic and dipolar forces. The paradigm is to create supramolecular materials with desired function and programming their assembly *via* intermolecular interactions.

Supramolecular perception of chemistry has generated a paradigm shift from focus on covalent interactions in discrete molecules to non-covalent interactions among them. It has led to dissolution of traditional boundaries between different classes of chemistry (organic, inorganic, biological, materials, etc.) Originally, supramolecular chemistry was employed to create enzyme mimics, macrocyclic host-guest systems, translation and transcription of genetic codes, etc. However, it also finds applications in smart materials, nanocrystalline materials, gas adsorbents, sensors, storage devices, molecular switches, targeted therapeutics, and many more.[2]

1.2 CRYSTAL ENGINEERING – A CONCEPT

'... the understanding of intermolecular interactions in the context of crystal packing and in the utilisation of such understanding in the design of new solids with desired physical and chemical properties'

GAUTAM DESIRAJU, 1989 [3]

Crystal engineering is a branch of supramolecular chemistry that deals with rational design of functional molecules. It is an interdisciplinary field that encompasses all branches of theoretical and applied chemistry. It deals with the study of intermolecular interactions and the packing modes with respect to these interactions to define a definite design strategy. It also allows us to study the solid-state properties in the crystals and fine-tuning them according to the pre-desired applications. If the crystal structure of any molecule can be predicted, then in principle, the properties of that solid can also be controlled.[4–10] Moreover, the concept of crystal engineering combined with combinatorial chemistry has led to development of many new disciplines in material sciences; the former focusses on structural aspects of a solid and the latter is concerned

with automation of synthesis and screening of properties for a large group of compounds at a rapid rate.[11]

From organic chemistry point of view, crystal engineering can be considered as supramolecular retrosynthesis from synthon approach; it can also be considered as crystal design based on hydrogen bonds and intermolecular interactions from crystallography point of view. From materials perspective, we may call it an approach where we can manifest a range of desired properties in the solid. The identification of molecular groups containing specific functionalities in a molecule is the primary objective to understand packing characteristics in the crystal. This is because these units are involved in building up the crystal structure through a series of repetitive units, the supramolecular synthons (Figure 1.2).[12]

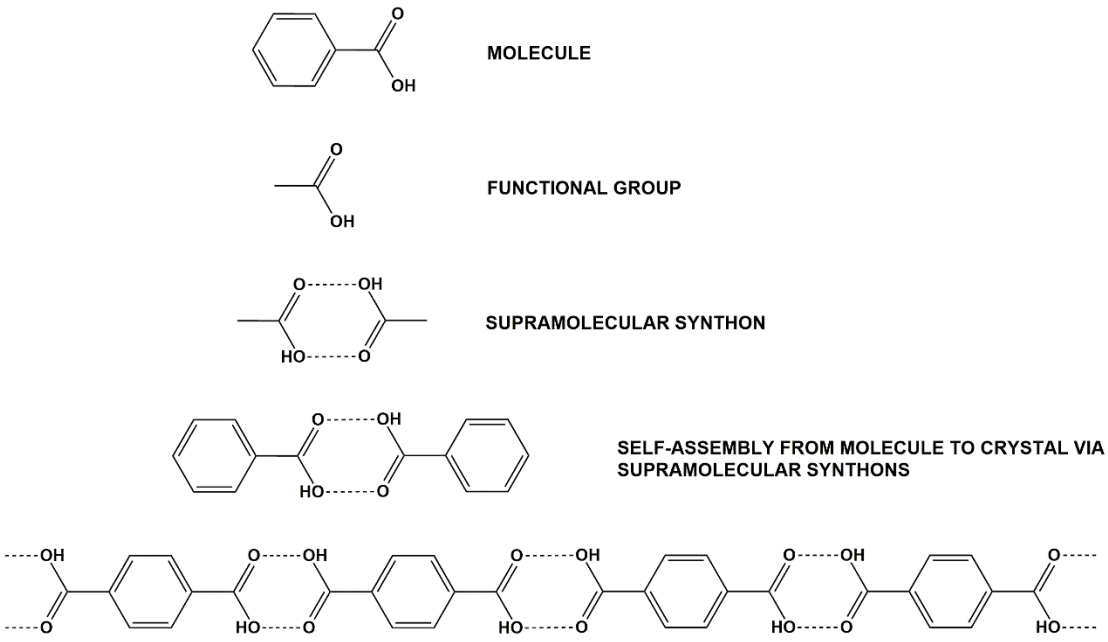


Figure 1.2 Self-assembly of molecules *via* supramolecular synthons to form a crystal structure

1.2.1 Control of molecular solids – Designer crystals

Crystallization of molecules in solution is considered a supramolecular process. It is strongly governed by thermodynamic and kinetic factors. Crystallization is a complex but highly efficient process where all the molecular groups compete with each other giving rise to several intermolecular interactions; however, the ones which are thermodynamically, kinetically or statistically sustained only can contribute in

formation of stable crystal structures. These stable interactions form robust synthons which immediately eliminates all the alternative possibilities. We can also correlate the processes between crystallization of small organic molecules and the folding of proteins. Both of them proceed through intermediate steps constituting of structure-determining clusters which finally result in causing either of the two processes.[13–15]

Crystal engineering remains at an intersection of structural and supramolecular chemistry. The concept of designer crystals has been long proposed, which concerns with the ability to design and control the ways in which molecules pack to give a crystal (Figure 1.3). It also concerns with the prediction of crystal structures of known molecules which can enable the identification of molecular precursors *via* retrosynthetic analysis of target molecules.[8] In that regard, organic crystal structure prediction (CSP) methods are available, which can screen for thermodynamically most stable crystal structure by making approximations in evaluating the crystal energy.[16] These methods are also used to establish different polymorphic forms of the same molecule, and hence solid-state properties. Even though these crystal energy landscapes have been crafted for not many molecular systems, they have successfully displayed different crystalline behaviors for sets of closely related molecules. But since the crystallization behavior varies from one molecule to another, CSP studies can be very beneficial in the study of polymorphic systems and prediction of organic crystal structures.

Figure 1.3 Occurrence of regular Platonic shapes in crystalline solids around us

With respect to creating designer solids, recently enough, elastic bendable crystals were discovered with exceptional flexibility and unique properties.[17] Although followed by a serendipitous discovery, they have sparked tremendous interest in the design of mechanically adaptable soft crystalline materials. A combined study of mechanical flexibility *via* crystal engineering approach can guide our way to create novel systems with extraordinary applications. They have already been proposed for creating flexible optoelectronics, semiconductor devices, actuators, artificial muscles, etc.

1.2.2 Intermolecular interactions

Intermolecular interactions are the attractive and repulsive interactions that prevail in a stable molecule. The understanding of these interactions in a solid constitutes the primary step in the control of molecular organization.[13] Intermolecular interactions are classified mainly in two classes –

1. *isotropic/medium-range forces*, which define the shape of the individual molecules, as well as their size and close packing (e.g., C…C, H…H, C…H).
2. *anisotropic/long-range forces*, which originate from electrostatic interactions (like the hydrogen bond) and determine intermolecular orientations (e.g., O–H…O^- , N–H^+…O^- , O–H…O, N–H…O)

There are also *strong metal– metal bonds and metal–ligand coordination bonds*. Other than the robust metal-metal and metal-ligand bonds, metal complexes can attain extra stability due to weak intermolecular interactions, esp. when the ligands constitute a significant amount of organic backbone.

The anisotropic interactions involve partially charged atoms, such as oxygen, sulphur, nitrogen, phosphorus and chlorine, whereas isotropic interactions include van der Waals forces, which prevail among all atoms and molecules. These forces can be attractive or repulsive depending on the distance between the interacting atoms. Although these forces are individually weak — they have bond energies between 8-10 kJ/mol as opposed to 400 kJ/mol of covalent bonds. For instance, the three-dimensional shapes of biomolecules, such as proteins and enzymes, are the result of medium-range intermolecular interactions. In nutshell, all molecular recognitions can be said to arise from isotropic interactions, but the directional effects and their function depend on the anisotropic interactions.

Among these, hydrogen bonding is considered to be the most important interaction in crystal chemistry. It provides robustness to the crystal structure in terms of strength and directionality. It can have energies in a range of 12-30 kJ/mol, and both the strong and weak hydrogen bonded interactions are involved in the crystalline self-assembly. It is also believed that the weaker hydrogen bonds provide structural adaptability and improved stability. According to Prof. Desiraju, "*the hydrogen bond is a complex and composite interaction*".[18] Complex, because it is made up of atoms within the interaction system, X—H…A; composite, because it comprises of three main ingredients – covalency, electrostatics and van der Waals character. While strong hydrogen bonds can be observed in any system, the weak hydrogen bonds may only be observed in crystals. The bonds like N—H…O and O—H…O are electrostatic in nature, while the CH_4…Ar or C—H…F—C constitute the weak interactions owing to their dispersive nature (Figure 1.4).[19]

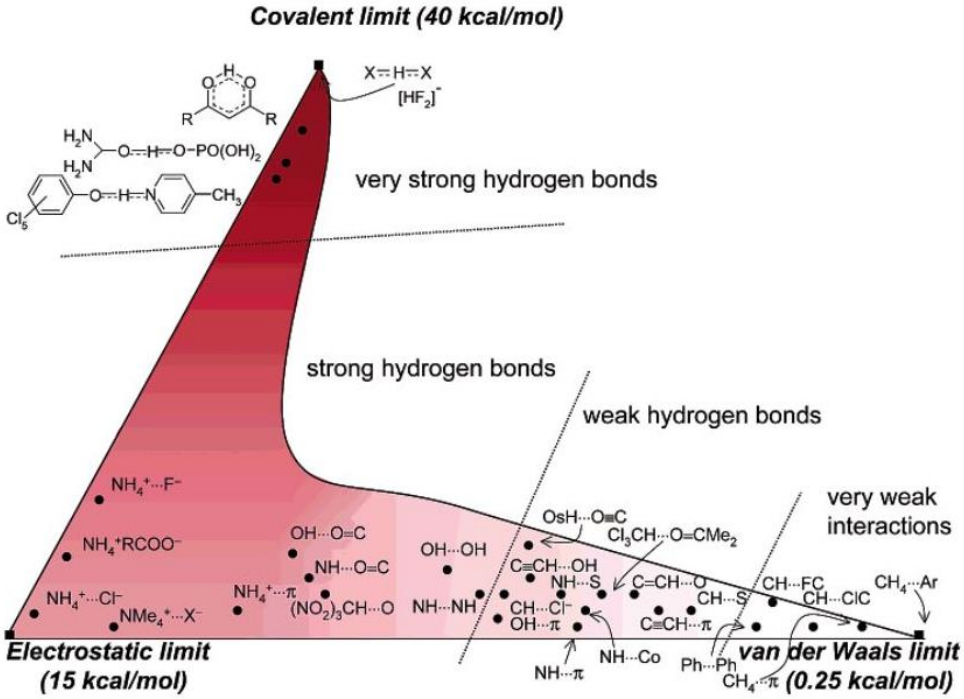
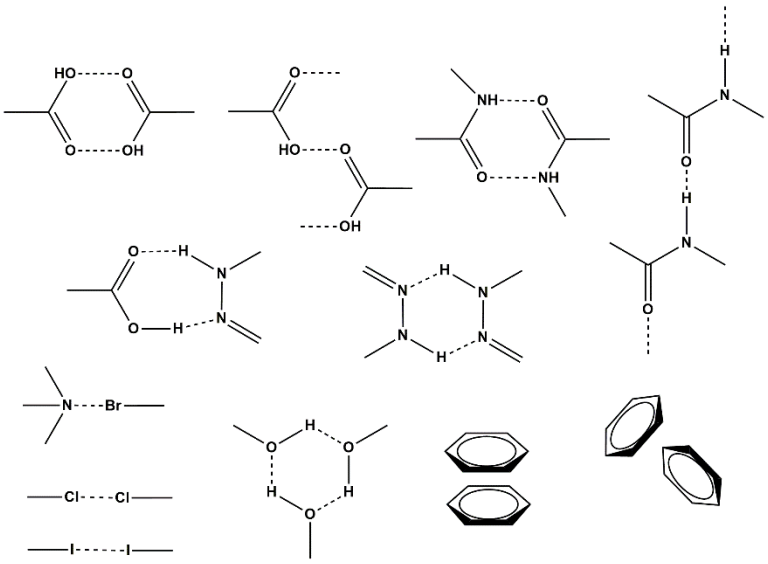


Figure 1.4 The hydrogen bridge reported by Prof. Desiraju. Adapted with permission from ref.[18]. Copyright 2022 American Chemical Society

In crystal engineering, the idea is to design and control packing arrangements to create crystals with definite properties. There has been a massive surge in the development and understanding of well-known (e.g. halogen and hydrogen bonds) and not so well recognized supramolecular interactions that govern the packing in crystals, such as anion-π interactions, chalcogen bonds, pnictogen bonds, π-hole interactions[20], etc.[14] This ideally starts with finding recurring packing patterns adopted by the functional groups in hand and relying on the robustness of their motifs to create new solid-state structures. These small repetitive units are called supramolecular synthons.

Supramolecular synthons *are structural units within supermolecules which can be formed and/or assembled by known or conceivable synthetic operations involving intermolecular interactions.*[21] They are representative of spatial arrangements of intermolecular interactions and exemplify a retrosynthetic approach which involves breaking the crystal structure into supramolecular synthons and depending on their robustness and stability, design strategies for new systems can be formulated.[22] This concept has evolved over the time, from supramolecular synthons being synthetic subunits to basic units for understanding the dynamics of crystallization. They are inherently modular in nature and offer more versatility in the field of crystallography than ever before. Some representative synthons are shown in Scheme 1.1.



Scheme 1.1 Some supramolecular synthons observed in crystal structures

1.2.3 Hirshfeld surface analysis

Hirshfeld surfaces were reported for the first time in 1998 by Spackman and coworkers.[23,24] They offered a new way of exploring molecular crystals by isosurface rendering of smooth, non-overlapping molecular surfaces which arise from partitioning of crystal space based on Hirshfeld's stockholder partitioning scheme. These surfaces reflect the proximity of neighboring atoms and molecules, and hence the intermolecular interactions in a visual manner where the molecular shape can be traced in the crystal environment. We can obtain 3D isosurface images of the molecular surfaces, called the Hirshfeld surfaces and also quantify all the intermolecular interactions in the structure. They can also be utilized to analyze the structures of polymorphs and their arrangement of molecules. The 2D fingerprinting plots are obtained as a function of distances from the Hirshfeld surface to the nearest nucleus inside the surface (d_i) and outside the surface
(d_e).

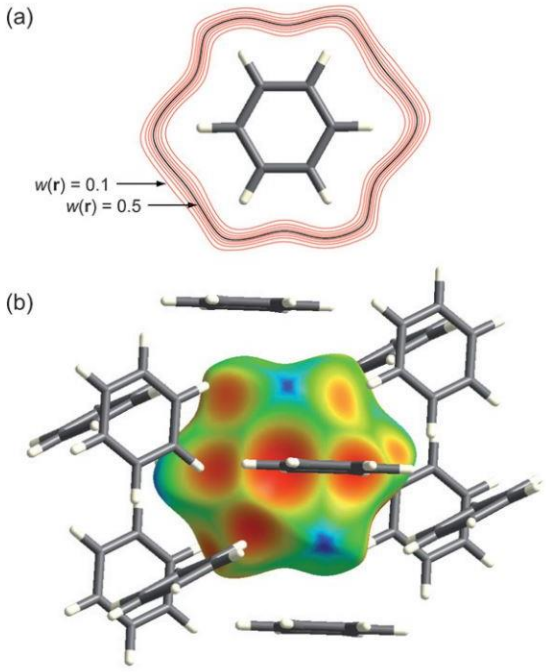


Figure 1.5 (a) Contours of $w_A(r)$ surrounding a benzene molecule in the crystal; (b) Hirshfeld surface for benzene mapped with d_e. Reported by Spackman and Jayatilaka. Adapted with permission from ref.[25]. Copyright 2022 Royal Society of Chemistry

The authors demonstrated the contours of weight function of atom A, $w_A(r)$ surrounding a benzene molecule (Figure 1.5).[25] These contours are closely spaced and surround the molecule in the vicinity of van der Waals surface. This makes the weight function extremely flat across the molecule. This isosurface envelops the molecule and defines the volume of space where the pro-molecule electron density exceeds from all neighboring molecules – this guarantees maximum proximity of neighboring molecular volumes, but the volumes never overlap because of the nature of the weight function.

The software developed for mapping Hirshfeld surfaces is called *CrystalExplorer* [26]. It also utilizes computational tools to compute *ab initio* wavefunctions for the molecules, which can also be used to map electrostatic potentials on these surfaces.[27,28] It can be applied to a wide range of molecular crystals such as neutral organic molecules (including other p-block elements), metal coordination compounds, organic salts, solvates and radicals. The computational and graphical tools provided by the software significantly enhance our understanding of the intermolecular interactions in context of crystal packing. The authors have proposed that this software can be further improvised to explore the lattice energies and mechanical properties of the crystals.

1.3 SUPRAMOLECULAR GELATION

'... the colloid condition, the gel, is easier to recognize than to define'

DOROTHY JORDAN LLOYD, 1926 [29]

Supramolecular gels belong to the class of soft materials, which can display both, solid- and liquid-like properties under the influence of external mechanical stress. They are typically dilute systems containing a very small amount of Low Molecular Weight Gelator (LMWG or LMOG) which can self-assemble into nano-scale network causing the solvent phase to immobilize, forming a gel. This happens as a result of a combination of complementary supramolecular interactions such as electrostatic, hydrophobic, van der Waals, hydrogen bonding, π-π, etc. to generate hierarchically ordered supermolecules. They are viscoelastic and thermoreversible, owing to the formation of self-assembled 1D fibers which interact *via* non-covalent cross-linked interactions and form a three-dimensional sample spanning network.

A cooperative effect of hydrogen bonding, van der Waals interactions, C-H…π, π…π stacking, charge transfer, electrostatic and dipolar forces, and similar interactions are responsible for promoting preferential 1D growth of fibers. These anisotropic fibers lay a foundation for designing new gelation systems for desired applications. Even then, gelation largely remains an empirical phenomenon, where most of the gelators are discovered serendipitously, even today!

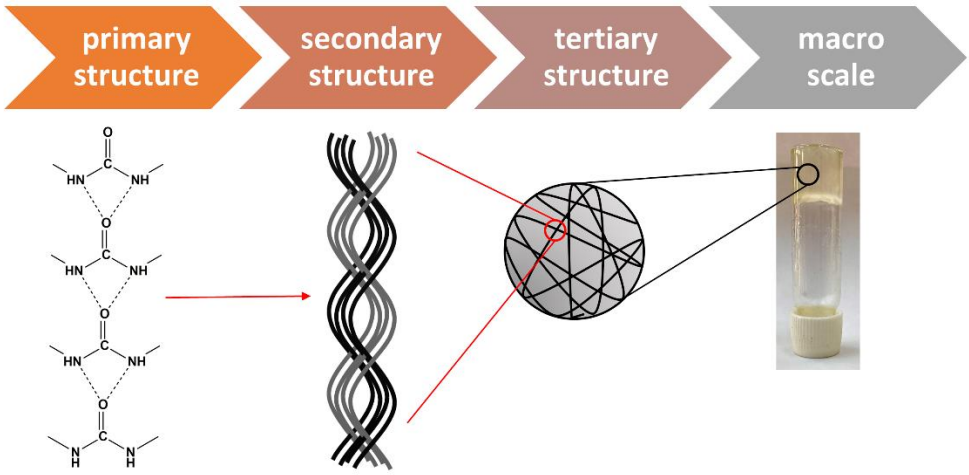


Figure 1.6 Hierarchical self-assembly in *bis*-urea based moieties

The mechanism at molecular level is not even fully understood till today. As was rightly quoted by D. J. Lloyd, "***the colloid condition, the gel, is easier to recognize than to define***".[29] This, however, seems to be a typically colloquial statement, as not all gels are colloidal and not all colloids are gels. Even though, after numerous such attempts to define and characterize such complex soft materials, Ferry offered a more descriptive definition of gels, "***a substantially dilute system which exhibits no steady state flow***."[30] Based on the attempts to propose more suitable definitions of gels, it was proposed that

"*a substance is a gel if it 1. has a continuous microscopic structure with macroscopic dimensions that is permanent on the time scale of analytical experiments and 2. is solid-like in its rheological behavior despite being mostly liquid* ".[31]

Anyone can identify a gel but defining it from a scientific point of view is never easy. In the last decades, gels have attracted a rapidly growing interest mainly because of their potential applications and their impressive behavior. The fact that the self-

assembly process ideally initiates from a single molecule and causes the formation of 1D fibers (typically in the range 5-100 nm) and eventually an entangled network capable of immobilizing solvent molecules is a particularly distinct feature of gels. They arise from a self-assembly across many length scales and essentially comprise of ~ 99% by mass of the liquid phase (Figure 1.6). Also, it has been reported that the networks formed by organogels consist of well-ordered arrays of molecules arranged in different architectures, such as rods, tapes, fibers, sheets and cylinders.[32–37]

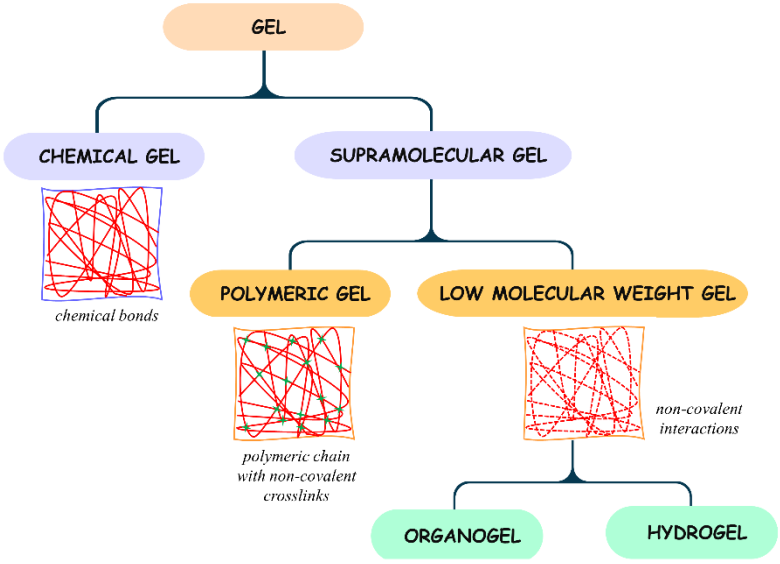


Figure 1.7 Classification of gels based on intermolecular interactions and nature of gelators

Gelation is often considered analogous to precipitation, the only difference being, it is driven by non-covalent interactions in a single dimension.[38] Gels derived from small molecules having molecular weight <2000 are typically considered as supramolecular gels; as they are formed by the virtue of supramolecular self-assembly to form SAFiNs (Self-Assembled Fibrillar Networks) purely governed by non-covalent interactions like H-bonding, π-π interactions, metal coordination, solvophobic forces, donor-acceptor interactions, van der Waals interactions, etc. (Figure 1.7)[36,39–41]

LMOGs capable of congealing organic solvents are popularly known as organogelators, while those which can gel water are called hydrogelators. Typically, hydrogels find significant role in a variety of applications such as drug delivery systems, tissue engineering, optics, diagnostics and imaging.[42] Most commonly employed systems for

the development of hydrogels are peptide amphiphiles, polysaccharides, natural acids and polymers.

Among these, the peptide-based hydrogels are most sought-after as they are –

- biocompatible and biodegradable
- non-toxic
- form porous and elastic networks which can hold large amounts of water
- easy to gel at normal room conditions and
- highly responsive.[43]

Supramolecular gels are ubiquitous and an indispensable part of our daily lives. They are highly functional materials which can respond to external stimuli like heat, light, ultrasound, change in pH, presence of redox-active species, ions, enzymes, applied voltage, magnetic field, etc. The area of molecular gels has expanded manyfold since its inception and it is believed that their key advantages like exquisite tunability, self-healing ability and self-programmability can guide our way to design such functional materials *a priori*, which has so far, remained a challenging task.

1.3.1 LMOGs based on molecular design

Designing molecular gelators *a priori* with the current understanding of structure-property relationship has remained a challenge since decades. Though a plethora of small molecules have been established as LMOGs with potential applications (Figure 1.8), the grassroot fundamentals at molecular level still remain limited. This is mainly because of the fact that many diversified molecules serve as gelators for a diverse range of solvent systems.

Some of the most well-known gelators reported in literature have been discovered serendipitously. Weiss and co-workers reported gelation behavior of ALS (anthryl-linker-steroid) based compounds in 1989.[44] This further led them to discover numerous such systems with exceptional gelation behavior in the following years. It was a breakthrough in true terms as it made us aware of the prerequisites for inducing gelation–

- strong and directional supramolecular interactions for promoting aggregation of the gelator molecules to form fibers;
- ability to form entangled fibers (SAFiNs);
- factors preventing neat crystallization of the gelling agents.

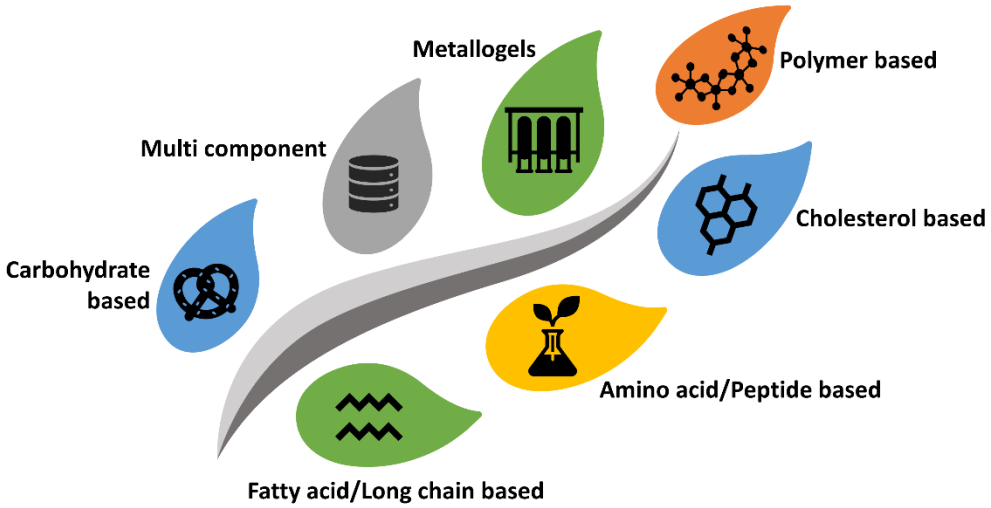


Figure 1.8 Types of low molecular weight gelators

It also highlighted the importance of hydrogen bonding in mediating the self-assembly process. To quote Prof. Weiss, "*Appropriately designed 'small' molecules can self-assemble into networks that encapsulate large volumes of liquids, thus producing gels*".[45] Small molecules capable of exhibiting gelation behavior if designed rationally, employing the principles of gelation mechanism and molecular engineering approach, can open up new avenues for creating functional systems with desired properties.

1.3.1.1 Fatty acids/long aliphatic chain based gelators

Long chain or fatty acid based amphiphiles have been exploited for gelation behavior since many decades. They have shown gelation in a wide range of solvents. Many of these fatty acids have been studied for their ability to store lipids and their physiological effects associated with cell stability. They are biocompatible, inexpensive, and environmentally benign. Various examples of such gelation systems containing saturated, unsaturated, substituted, modified backbones, multiple functional groups, and various functional groups such esters, amides, urea moiety, salts, metal complexes are available. The most infamous of them is the case of HSA (12-hydroxystearic acid). It can congeal a variety of solvents at remarkably low concentrations. This unique property arises from its chemical structure, which comprises of a long aliphatic chain, a secondary hydroxyl group and a carboxylic head group. All of them combined make the perfect balance of hydrophilic and hydrophobic forces required for the formation of SAFiNs in all types of solvents.

These gels have been widely applied for their use in creating smart responsive materials, adhesives, inks, plasticizers, paints, coatings, etc.[46,47]

1.3.1.2 Carbohydrate/sugar based gelators

The self-assembly of sugar based gelators have received a lot of attention as they are often biodegradable, non-toxic, and ecofriendly which make them ideal candidates for biomedical applications. It is also known that carbohydrate-protein interactions play an important role in biological phenomena like blood coagulation, immune response, viral infection, inflammation, embryogenesis, etc. Several synthetic strategies have been developed and reported in literature to create such gelation systems with mono-, di- or polysaccharide units. Moreover, the precursors required for creating such systems are inexpensive and commercially available. Some of the most commonly employed backbones are D-glucose, D-sorbitol, D-maltose, D-galactose, D-mannose, D-allose, L-ascorbic acid, trehalose, amygdalin, all of which can be extracted from natural sources. These systems are highly versatile and find applications in stimuli-responsive systems, oil spill remediation, separation of proteins, optical devices, self-healing, nanoparticle synthesis and many more.[48–50]

1.3.1.3 Amino acid/Peptide based gelators

Peptide based scaffolds are known to exhibit exceptional hydrogelation and organogelation behavior. They can self-assemble *via* various interactions like hydrogen bonding, electrostatic or π-π to form organized supramolecular structures that can entrap and immobilize many solvent molecules under appropriate conditions. The most important application of these systems is creating peptidomimetics, systems which are designed to mimic natural peptides with enhanced properties like higher proteolytic stability, higher bioavailability and improved selectivity or potency.[43,51,52]

1.3.1.4 Two-component/Multi-component gelators

Multi-component gels offer a facile way to create systems with tailor-made properties. They allow us to finely control the properties of the gels by adjusting the assembly of one of the components. They find a special place in LMOGs mainly because –

- simplicity of the system to understand the mechanism of gelation, especially, when the number of non-bonded contacts are limited
- multiple functionalities can be envisaged in a single system by suitable choice of individual components and
- crystal engineering approach can be applied successfully to design a new multi-component gelator.[53]

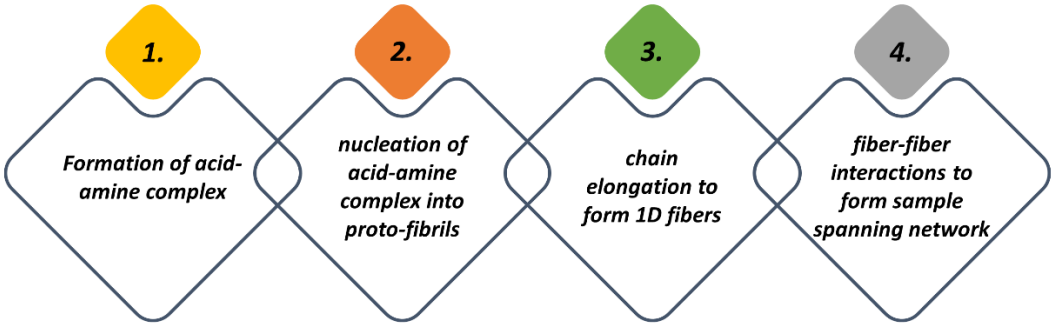


Figure 1.9 Multi step gelation process in acid-amine systems

There are various ways of designing multi-component LMOGs, although the basic principle remains the same in all classes, two or more compounds must form a complex in order to form a gel.[38]

These are highly tunable systems with a possibility to obtain a high degree of morphological and functional control (Figure 1.9). Based on design, two-component systems can be classified in three different groups:

1. where neither of the compounds can form gels in their own right but combine together to form a self-assembly
2. where both compounds form gels in their own right. In such systems, either (a) both gelators interact with each other to form co-fibers or (b) the two gelators self-sort resulting in two different nanofibers within the gel
3. gelator plus additive component gels where one compound is a gelator and the other molecule is non-gelling and is designed to impact the gel's thermomechanical or functional properties by, for example, impacting the assembly of the gelator or inducing certain desired properties in the gel.[54–56]

1.3.1.5 Cholesterol/Anthryl (ALS) based amphiphilic gelators

The cholesterol moiety is one of the most versatile units to have shown gelation behavior in a variety of solvents. The cholesterol molecule has a fascinating structure, where the aliphatic rings (three six-membered and one five-membered) are fused and locked together in *trans* fashion. The cyclohexane rings remain locked in a chair conformation which allows the molecule to obtain a rigid and flat structure. It resembles closely to a surfactant molecule, but it does not behave as one, as it cannot form self-aggregated assemblies on its own. Also, cholesterol is a non-gelator in its own right. Cholesterol based gelators were reported for the first time by Weiss and coworkers, where they demonstrated an ALS (anthryl-linker-steroid) based design for LMOGs with a variety of applications.[44] Since then, many such systems have been designed and synthesized which hold great potential for creating new functional materials. Cholesteryl gelators containing chromophoric units have been designed which have been used for various optoelectronic applications such as LEDs, fluorescent sensors, artificial photosynthetic systems, and many more. They have also been explored for photovoltaic applications, oil spill remediation, host-guest recognition, templated synthesis of inorganic nanostructures, etc.[57–61]

1.3.1.6 Metallogels

Metallogels form a unique class of supramolecular gelators which comprise of discrete metal coordination complexes, coordination polymers, etc. Their chemistry is considered to be different than that of conventional organogelators as it is believed that they involve unique metal-metal interactions which can act as driving forces to give additional stability to the metallogels. They are essentially formed by virtue of metal-ligand bond formation and offer potential applications in designing sensors, catalysts, magnetic materials, redox systems, etc.[62–64]

1.3.1.7 Polymer based gelators

Polymer gels are formed by irreversibly crosslinked networks. This crosslinking can occur *via* polymerization of monomers or through covalent bond formation between various polymeric chain, often triggered by irradiation or addition of activators. There are certain polymeric gels which contain physical networks that form non-permanent

thermoreversible gels. They have been utilized for very specific applications, especially in the biomedical field, such as, tissue development, biosensors, radiation dosimeters, and many more. They are also exploited for their use in creating hybrid gels containing multi-component systems comprising of an LMOG or a non-gelator and a polymeric gelling moiety. [65]

1.3.2 Characterization of supramolecular gels

The dynamic nature of the intermolecular interactions that govern the self-assembly of gelators make the characterization of gels in their native state extremely challenging. A combination of different techniques is ideally required to cover various aspects of gelation. This not only improves our understanding of the material properties of molecular gels, it also enables the use of these systems for various applications.[66–69]

1.3.2.1 Inverted vial method

While there are a variety of techniques available for characterization of gels on macroscopic, microscopic and nanoscopic length scales, the simplest and preliminary characterization of a gel involves a critical visual inspection, to identify whether the sample exists as a sol, gel, or a viscous liquid. Inverted vial method involves taking known amounts of gelator and solvent in a glass vial and heating the mixture to obtain a clear solution. This glass vial is ideally cooled for 24 hours (or overnight). An absence of flow of the semisolid mass evolved on inversion of the glass vial indicates gel formation. The minimum amount of gelator required to gel 100 mL of solvent is calculated and reported as mgc/cgc (minimum/critical gelator concentration, %wt, w/v) value.

1.3.2.2 Microscopy

Microscopy is one of the most convenient techniques employed to capture the gel structure as it allows visualization of the individual gelator fibers which contribute to the formation of SAFiNs. The most commonly employed microscopic techniques are, electron microscopy, Super Resolution Microscopy (SRM) and Scanning Probe Microscopy (SPM). Scanning Electron Microscopy (SEM) and Transmission Electron

Microscopy (TEM) offer high-resolution imaging of the molecular gels and help in visualization of overall 3D assembly. However, it is widely believed that dried gel images fail to represent the molecular self-assembly present in the gel form. Cryogenic SEM or TEM offer an edge in that regard, since the sample still remains in a nearly solvated environment. Gels have displayed a variety of structural diversities, like tubes, fibers, helical structures, ribbons, plates, etc. However, more sophisticated microscopic techniques like Confocal Laser Scanning Microscopy (CLSM), Stimulated Emission Depletion (STED) Microscopy, Stochastic Reconstruction Microscopy (STORM) have opened new arena in the field since they are capable of displaying self-sorted fibers in gel form itself. Atomic Force Microscopy (AFM) is an SPM technique, used to visualize gel fibers and analyze their morphology, surface, height of the fibers, etc. It uses a probe which physically moves over the sample to generate an image and obtain information from the sample surface. Polarizing Optical Microscopy (POM) is a widely used technique for characterizing liquid crystalline gels or those possessing birefringent character.

1.3.2.3 Rheology

Rheology is the study of deformation of a material under applied stress or strain. Since gels are viscoelastic materials, they exhibit the properties of both, solids, and liquids. Gels, when subjected to external stress, tend to become less viscous. This phenomenon is called thixotropy. Rheology, by far, remains one of the most important techniques for identification of gels. There are two ways to conduct a rheology experiment, varying the frequency at a fixed amount of amplitude of stress, or by using a fixed frequency and varying the amplitude of shear stress. For any material to be classified as a gel, the value of storage modulus (G′) should be more or less constant with increase in frequency up to a certain point and should exceed the value of loss modulus (G″) by at least an order of magnitude. G′ represents the amount of energy that can be stored in the gel, which indicates elasticity of the sample, G″ symbolizes the tendency of the material to flow. Thus, for an ideal solid, G″ = 0 and for Newtonian liquids, G′ = 0. For viscoelastic materials like gels, the dominant elastic behavior of the system is highlighted by G′ >> G″.

Depending on whether the molecular network in the gel is static or dynamic, gels can behave as viscoelastic solids or viscoelastic liquids. In case of static interactions,

frequency dependent behavior is not generally observed and hence, G′ > G″ at all frequencies. In case of dynamic systems, G′< G″ at lower frequencies and G′ > G″ at higher frequencies.[70,71]

1.3.2.4 Small angle scattering

Small angle scattering can be used to investigate the primary fibrous assembly of the gelator molecules. It is superior to microscopic techniques as it is non-destructive and can be directly carried out in gel samples. Small angle X-ray scattering (SAXS) can give information about crystal structure, chemical composition, and other physical properties of supramolecular gels. It can also provide important insights about molecular weight, intermolecular distance, average particle size, shape, etc. of the gelator.

Neutron diffraction is a type of elastic scattering technique where there is a constant exchange of neutrons of similar energies. This technique is similar to X-ray diffraction; however the unique properties of neutron diffraction allow for the classification of materials that have similar elemental compositions while providing improved resolution in the identification of materials where XRD is lacking. Small angle neutron scattering (SANS) is performed using a contrast, usually a deuterated solvent. The data is fitted to a best suited model, usually to a cylinder, flexible cylinder, hollow cylinder or a similar long, anisotropic structure. The fit also provides a tentative radius and length of the structure.

1.3.2.5 X-ray diffraction studies

X-ray diffraction essentially involves electromagnetic radiation, such as X-rays to bounce off the material and the diffracted X-rays are constructively coupled to enhance the intensity and directed towards the detector to gain useful insights regarding the characteristics of the material. They work best for crystalline materials, as they can assist in establishing the molecular structure, packing and intermolecular interactions possibly governing the self-assembly of the gelator fibers. Powder diffraction is more commonly used, as it can accommodate samples in powder, film, or bulk form. Small-Angle X-ray (SAXS) and Wide Angle X-ray (WAXS) techniques are increasingly used for the characterization of gelation systems. These days, XRD coupled with synchrotron

is performed to obtain superior resolution and tunable radiation over a range of wavelength.

1.3.2.6 NMR spectroscopy

NMR spectroscopy can be used to gain information about structural properties of the components, their aggregates, and their interactions, which play an important role in formation and stability of the gel systems. It can be used to follow the gelation kinetics, as in solution state, the molecules can be detected by NMR, while in gel form, the molecules transform into fibers and hence become NMR invisible. There are various instances where NMR techniques have proved to be powerful to study the gels on a molecular scale and indicate the formation of hydrogen bonded assemblies, which were responsible for triggering gelation behavior. VT-NMR is a very sensitive technique to study the sol-gel transitions for temperature sensitive systems. At low temperatures, the ^{1}H NMR signals are essentially weak, which suggests strong intermolecular assembly, and as the temperature is raised, gradually the peaks start to appear as the gel converts into sol. It can provide essential information regarding the kinetics of gelation on molecular scale.

1.3.2.7 Computational modelling

Computational modelling can efficiently help investigate the molecular packing in self-assembled systems. It can also help us visualize the stacking of molecules which form fibers and eventually trap solvents, forming gels. The data obtained is generally used to follow the self-sorting process of the fibers. The technique still remains in its infant phase, since the calculations become more and more computationally expensive with increase in number of molecules. The system becomes more complicated with inclusion of solvent environment and higher computational methods. However, the technique has proved to be very useful in systems where single crystal studies of gelator molecules could not be performed, as is the case with most of the gelation systems.

1.3.2.8 Other methods

Gelators capable of undergoing electronic transitions can be characterized using UV-visible spectroscopy. Molecules containing π-electrons or non-bonding electrons can absorb the energy in the form of ultraviolet or visible light and excite these electrons to higher anti-bonding molecular orbitals. UV-vis spectroscopy is widely used for quantitative determination of analytes and for the characterization of gels as it can identify the non-covalent interactions and changes in hydrophobic environment.
Fluorescence spectroscopy is a complementary technique; it can be used where the species can be excited to absorb a photon, from its ground electronic state to a vibrational level of the excited state. The molecule then drops down to one of the ground state vibrational levels, accompanied by emission of the previously absorbed photon. These emitted photons have different energies, and hence, different frequencies which can be analyzed using fluorescence spectra.

Circular Dichroism (CD) is a spectroscopic technique which corresponds to differential absorption of left and right circularly polarized light. It can assist in the study of stereostructures and inter- and intra-molecular interactions in chiral assemblies. It is a non-destructive and sensitive technique that makes a powerful tool in the structural analysis of chiral systems.

Fourier Transform Infrared (FT-IR) spectroscopy works in a similar way as the above-mentioned techniques, where a difference in spectrum for the mixed system compared to those of the individual components can indicate a co-assembly. It can also provide useful insights on the type of interactions, the stacking among molecules, formation of fibrous assembly, etc.

Dynamic Light Scattering (DLS) is a technique especially useful for determination of size distribution profile, structural formation and interactions among the molecules forming 3D assemblies in the solution. It can also analyze temperature-dependent stability as well as the diffusion coefficient of the particles.

Differential Scanning Calorimetry (DSC) is a thermoanalytical technique which can measure the amount of heat required to increase the temperature of the sample against a reference standard, as a function of temperature. As the sample undergoes phase transformation, depending on whether the process is endothermic or exothermic, heat

is absorbed or released with respect to the reference to maintain both at same temperature. It is believed that gelation is a highly controlled crystallization process driven by non-covalent interactions, with crystal growth only occurring in one dimension. Thus, an exothermic peak can be monitored as the gel undergoes gel-to-sol transition because it requires more heat flowing to the sample to increase its temperature at the same rate as the reference. The enthalpy of the gel-to-sol transition can also be calculated from the DSC curve by integrating the peak corresponding to a given transition.

Many new innovative techniques have been proposed, such as Single Molecule Force Spectroscopy (SMFS), a developing technique based on AFM, to study the supramolecular polymerization driven by multiple host-stabilized charge-transfer interactions[72]; Electrospray Ionization Mass Spectrometry (ESI-MS) to visualize aggregates of complexes in solution, which gave evidence for the formation of metallogel[73]; MALDI-TOF-MS for the detection of organometallic gels[74], etc.

1.3.3 Employing solubility parameters to predict gelation

Gel formation usually follows a multi-level self-assembly process[75] driven by a complex interplay of intermolecular interactions and a meticulous balance between the gelator-gelator and solvent-gelator interactions. It is noteworthy that inter-gelator interactions are primarily involved in the preferential 1-D growth of fibers which promote gelation behavior and the solvent-gelator interactions play an important role in mediating the self-assembly of the gelator molecules. Also, as gels are considered to be typically dilute systems, where the solvent phase constitutes about 99% of the gel composition, the nature of solvent can greatly influence gelation behavior.

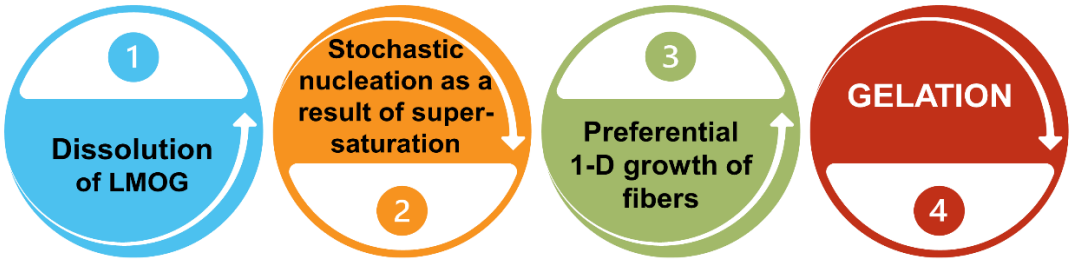


Figure 1.10 Plausible mechanism of gelation

Distinguishing gelators and non-gelators solely based on their intermolecular interactions and structural assemblies can be inappropriate. However, there have been various reports where correlation between thermodynamic dissolution parameters and gelation behavior have been established. Solubility parameters have been widely applied on the gelation systems to understand the underlying mechanism (Figure 1.10).

While conducting gelation trials on a set of compounds can be a time-consuming task, the solubility parameters can assist in rationalizing the gelation behavior. Many attempts have been made to correlate gelation parameters with empirical solvent parameters; and molecular level insights can effectively assist in establishing essential ground rules. The global solvent parameters (where a single parameter is used to characterize the solvent as a macroscopic continuum) are subdivided into three major categories as shown in Figure 1.11.

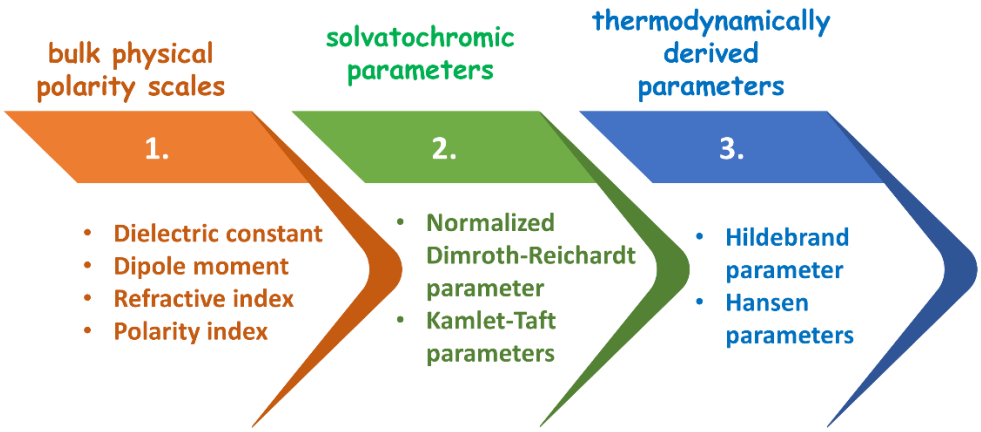


Figure 1.11 Solvent parameters employed in gelation systems

Physical solvent properties. This class characterizes the solvents by their bulk properties; these include the dielectric constant ε, dipole moment- μ, refractive index- η_D and polarity index- ***P'***. The dielectric constant (also called static relative permittivity, ε) is the ratio of amount of electrical energy stored in a material by an applied voltage with respect to that stored in vacuum; the dipole moment, μ arises from non-uniform distribution of atomic charges in a system; the refractive index, η_D corresponds to the velocity of light in a particular solvent as compared to that in vacuum; and the value of polarity index, ***P'*** gives the degree of solvent-solute interaction.[76] Many studies have been attempted to correlate gelation with dielectric constant but the results have been

varied. These properties hold the propensity to govern the interaction forces between solute and solvent molecules, which are responsible for showing gelation behavior. As far as gelation is concerned, no known set of compounds have exhibited significant differentiation with respect to $\boldsymbol{\eta}$ values across a range of solvents.

Solvatochromic Parameters. Solvent polarity can also be measured using solvatochromic dyes. It has been known that a solvent can alter the absorption bands of a dye because of three factors –

1. Dipolar interactions between the solvent and dye
2. Changes in dipole moment of the dye arising from any optical transition, and
3. the Franck-Condon Principle.[77]

Solvatochromic techniques rely on change in the position of UV/vis absorption bands of a solvatochromic dye caused by the solvent in which it is dissolved.[78] These parameters include the Normalized Dimroth-Reichardt parameter, $\boldsymbol{E_T^N}$, which is responsible for all possible intermolecular forces between solvent and solute molecules and the Kamlet-Taft parameters, which characterize a solvent with respect to its polarizability- $\boldsymbol{\pi^*}$, H-bond donating capacity- $\boldsymbol{\alpha}$ and H-bond accepting capacity- $\boldsymbol{\beta}$.[76,79] The $\boldsymbol{\alpha}$ parameter is known to have a correlation with the gelling ability, the magnitude of $\boldsymbol{\beta}$ affects the stability of the gel and $\boldsymbol{\pi^*}$ value indicates the influence of fiber-fiber interactions.[80]

Thermodynamically derived parameters. These parameters rely on the molar Gibbs energy of mixing- ΔG_m, enthalpy- ΔH_m or entropy- $T\Delta S_m$ of either or both the components to define parameters for solvation. These include the Hildebrand parameter, $\boldsymbol{\delta_0}$ and the Hansen solubility parameters, $\boldsymbol{\delta_d}$, $\boldsymbol{\delta_p}$, $\boldsymbol{\delta_h}$, $\boldsymbol{\delta_a}$. The Hildebrand parameter, $\boldsymbol{\delta_0}$ is related to the cohesive energy which combines dispersion forces and polar interactions which determine whether a solvent will promote self-assembly or not.[80] In a study by Dordick and Zhu, they reported a correlation between the mgc values and the Hildebrand solubility parameter of the solvent for the first time.[81] Hansen solubility parameters (HSPs) segregate the energetics of interactions of solvent with a solute in three components- dispersive (E_d, arising from atomic forces like London dispersion forces, van der Waals interactions, etc.), molecular dipole-dipole (E_p, arising

from permanent polar cohesive energy) and molecular hydrogen bonding (E_h, an electron exchange term). The value of HSP is given by E-

$$E = E_d + E_p + E_h \quad \text{- (1.1)}$$

The geometric mean of the three interaction parameters of both the individual entities gives an idea about the interactive forces between them.[40,82] Raynal and Bouteiller were among the first few to investigate the HSP approach in formation of molecular gels.[83,84] The data can be plotted in the form of 2D or 3D plots (Teas plot) which can differentiate the solvents capable of gelation with the non-gelling ones.[76,79,85–89]

1.3.4 Applications of LMOGs

Gelation systems find applications in a variety of disciplines and have completely transformed the world around us (Figure 1.12). These include development of medical diagnostic sensors, selective host-guest complexes, enhanced materials in everyday life, medicine, tackling water pollution, treating oil spills, responsive materials, energy-storage devices, light harvesting systems, optic and electronic devices and many more.[90–96]

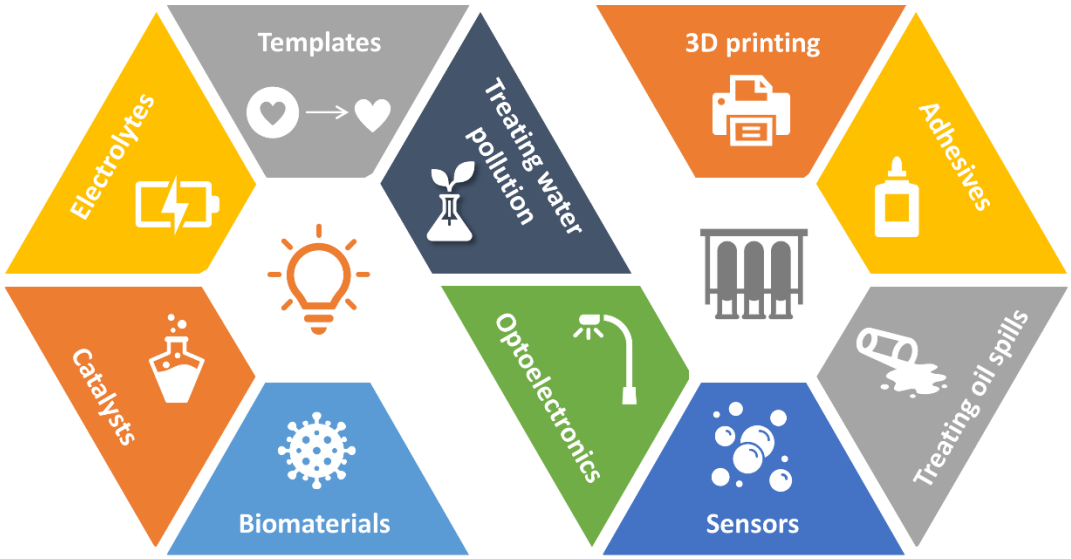


Figure 1.12 A graphic illustrating some of the infinite applications of LMOGs

1.3.4.1 Responsive materials

Responsive materials have been long known in the literature. It is the reversible sol-gel property of supramolecular gels that make them desirable candidates for creating responsive materials. External stimuli can be classified as physical and chemical; heat, mechanical forces, ultrasound, UV light can be classified as physical stimuli and change in pH, electrolytes, reagents, enzymes, metal ions, etc. classify as chemical stimuli (Figure 1.13). Also, combining more than one type of stimuli in the same species can result in formation of multi-responsive and multi-functional gels which can be employed to design 'smart' materials.[97–100]

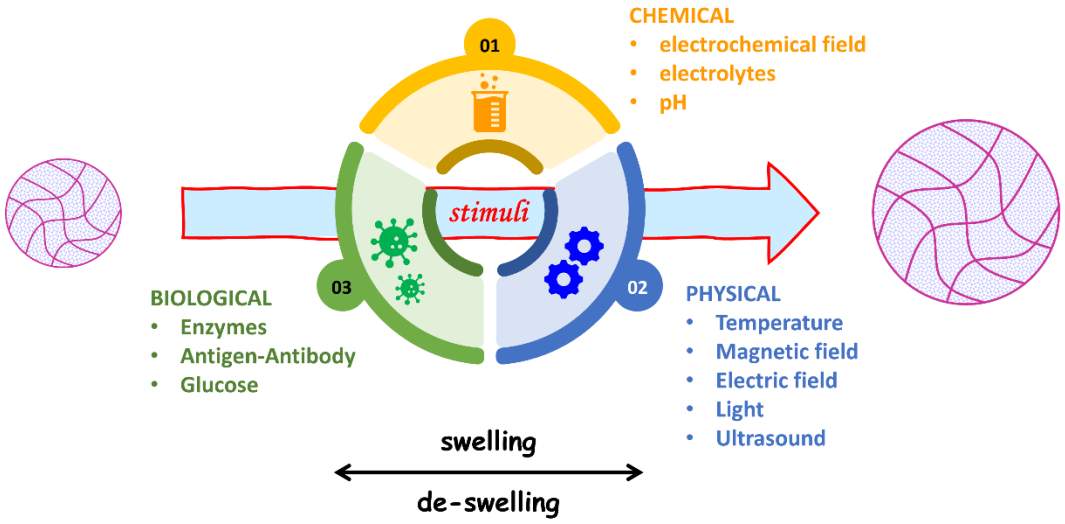
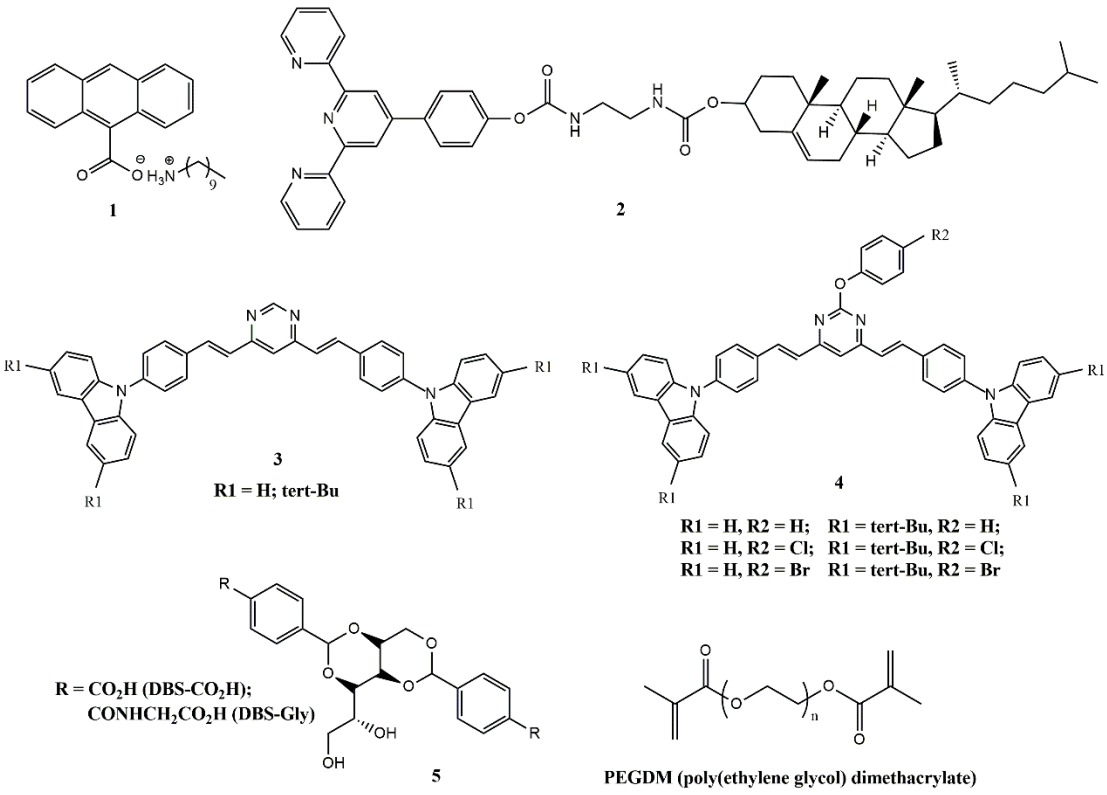


Figure 1.13 Response of gels to various types of stimuli

A simple molecule like melamine which is non-fluorescent in its own right, was identified as a potential molecule for inducing gelation as well as potential fluorescent properties in a melamine-quinazolinedione derivative complex by formation of a meta-stable excited state. The fluorescent properties of the complex also displayed a strong dependence on pH and temperature.[101] The most extensively studied photo-responsive materials are those containing anthracene and azobenzene type units in their backbone. Shinkai and coworkers exploited the photoinduced dimerization of anthracene units to trigger the sol-gel transition of N-decylammonium propionate and 9-anthracenecarboxylic acid (Scheme 1.2, **1**). This two-component gelator was found to undergo reversible gel-to-sol transition in cyclohexane on irradiation with Hg vapor

lamp at 15°C, which formed a non-gelling, dimerized product. On warming at 30°C, the dimer was dissociated and the gelator precipitated. On further dissolution, the gel could be reformed in the solvent.[102]

There is yet another class in stimuli responsive materials, the enzyme responsive gels. Enzymes are widely used to act as triggers for gelation/non-gelation and constitute the class of biological stimuli (Figure 1.13). In some cases, they are incorporated in the supramolecular assembly itself for enhancing the gelation behavior. Such systems find a variety of applications in drug delivery, antimicrobial applications, cell proliferation, bioimaging, etc. which have been discussed further in the chapter.



Scheme 1.2 Chemical structures of responsive gelators

A molecule containing terpyridine and cholesterol moieties was employed for its rigid core, fluorescent properties, and ion binding abilities (**2**). The idea of incorporating fluorophores in a gelation system can give rise to multifunctional systems which can be potentially explored for a variety of applications. The ethanol gel displayed self-healing properties owing to the presence of π-π stacking, hydrogen bonding and hydrophobic

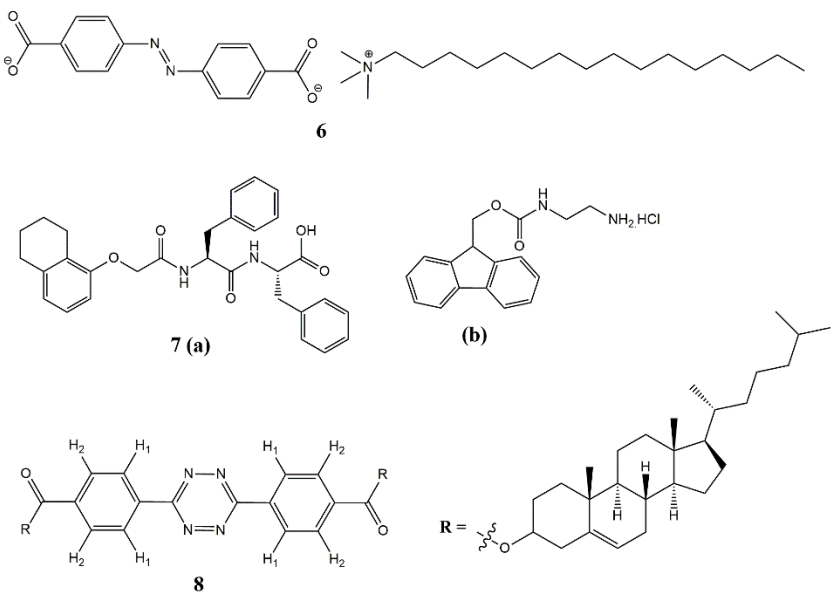
interactions. The terpyridyl moiety was found to be a promising motif for coordinating with metal ions like Tb^{3+}, Eu^{3+}, $Sn^{4+/2+}$, Cd^{2+} and Zn^{2+} with tunable wavelength and efficient energy transfer in gel state, where the gelator and metal ion solution were simply sonicated for a direct mixing to obtain self-healing, fluorescent gels.[103] These systems can have promising applications in development of responsive materials.

In an interesting study, a series of carbazole modified pyrimidine derivatives were reported for their organogelation and intense emission properties (**3,4**). From structural point of view, the authors reported that a V-shape structure and a π-conjugated skeleton were essential for gelation as they promoted superior π-π interactions which aided self-assembly. The authors discovered that the gel state could be completely destroyed in presence of trifluoroacetic acid (TFA). These gels were then utilized as sensors for TFA vapors with a fluorescence decay time of 0.6 sec and a detection limit of 95 ppb.[104]

In a unique study, Smith and coworkers reported two-component gelators containing two dibenzylidene sorbitol (DBS) moieties and a polymeric moiety (**5**, PEGDM). They achieved sequential self-assembly by controlled spatial and temporal application of physical and chemical triggers resulting into formation of a photo-patterned gel. High intensity UV-radiation was employed for physical trigger and three different types of chemical triggers were utilized–a photo-initiator (2-hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone), a chemical proton source (glucono-δ-lactone) and a photo-acid generator (diphenyliodonium nitrate). A careful combination of these triggers over space and time led to the formation of gels with four distinct domains containing varied amounts of self-assembled forms of the two major constituents (DBS moieties and PEGDM), where every gel sustained the history of each domain applied.[105,106]

Filippone and coworkers reported a two-component gelator containing an azobenzene moiety and a surfactant (Scheme 1.3, **6**). The system exhibited impressive hydrogelation at very low mgc values. The gels also showed self-healing properties after undergoing a stress-induced damage. The azobenzene moiety undergoes reversible light-induced isomerization from *trans* to *cis* form which provided the gel with light-responsiveness.[107] Azobenzene based gelators can be very useful in designing LMOGs that can reversibly assemble and disassemble under the influence of external stimuli. In a similar study, the authors designed and synthesized a series of azobenzene-modified cationic hybrid surfactants containing a fluorocarbon chain. The

molecules displayed exceptional ambidextrous gelation and multi-responsive behavior. The viscoelastic property of the gels were found be reversibly switchable on application of optical, mechanical and heating stimuli.[108]



Scheme 1.3 Chemical structures of responsive gelators reported in literature

With respect to multi-component gelators, Adams and coworkers reported a peculiar gelling system that exhibited pH-responsive behavior by virtue of assisted hydrogen bonding between the two components (**7** (a), (b)). The presence of carboxylic acid and amine groups in the two individual components allowed the gel to undergo unusual phase behavior, forming gels at both, acidic and basic pH. This was further supported by a change in molecular packing with a change in pH *via* coordinated hydrogen bonding interactions. The authors also presented an autonomous programming algorithm between the two pH-dependent gel states by incorporating an autocatalytic urease-urea reaction.[109]

In an interesting study, a liquid crystalline fluorescent gel was reported. The molecule consisted of tetrazine and cholesterol moieties (**8**). The gelation behavior was attributed to cooperative interactions between van der Waals forces of the cholesteryl ester group and π-π stacking of the diphenyltetrazine core. The molecule was also found to be possessing cytotoxic and antimicrobial properties which could be useful in development of drug delivery systems and bioimaging.[110]

1.3.4.2 Catalysis

In catalytic gels, supramolecular interactions are employed for the construction of a catalytic center. For instance, gelators are designed with a preliminary approach by combining an assembling fragment and a functional fragment. After gelation, the system will be containing very specific catalytic sites. This functional fragment can contain desired catalytic sites or pre-catalytic groups which can be activated after gelation. This is considered superior over conventional homogeneous/heterogeneous catalysis as after gelation, certain enhanced interactions among the fibers may promote better activity, substrate selectivity and cooperation. Also, a high degree of molecular order may additionally promote regioselective and stereoselective transformations.[111]

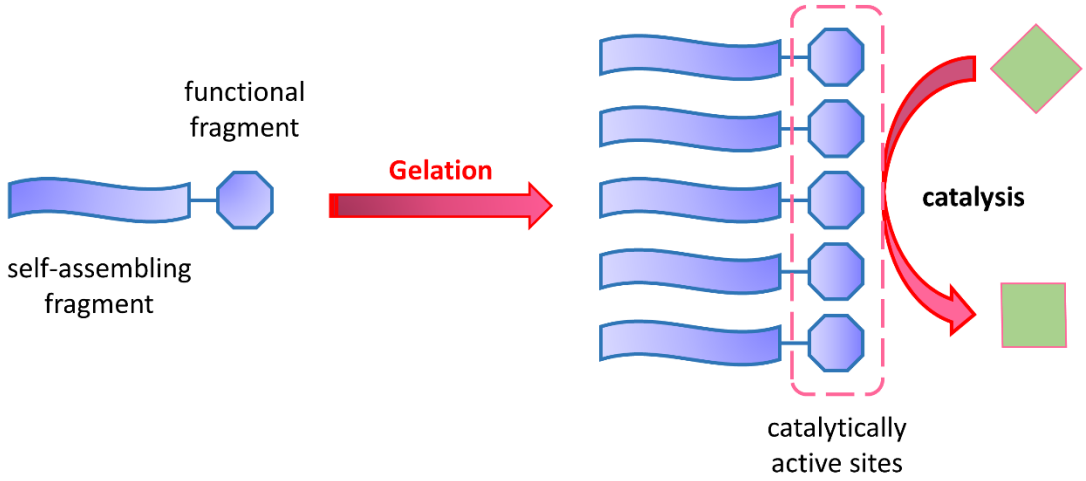


Figure 1.14 Designing catalytic gels

Although catalysis has been predominantly explored in polymeric gelators, LMOGs offer an edge in terms of providing a highly organized self-assembling process which can possibly control the orientation of the catalytic groups and bring them in a critical proximity, thereby improving the reactivity and performance of the catalyst. They find applications in being used as reaction vessels for synthesis of polymers with high molecular weight and low polydispersity index (Figure 1.14). In hydrogels, a high rigidity along with a strong hydrophobic environment favor the formation of high-molecular weight polymers.

Gels with catalytic moieties when covalently linked or embedded inside gelator molecules serve as catalysts for many organic reactions. In certain cases, enzymes were immobilized along with amino acid-based hydrogels which showed '*superactivity*' and high stability during catalytic oxidation reactions. This means that modifying the necessary nanofibers using self-assembly of hydrogels can be beneficial for enzyme catalyzed biotransformations. A possible explanation has been provided in literature as-

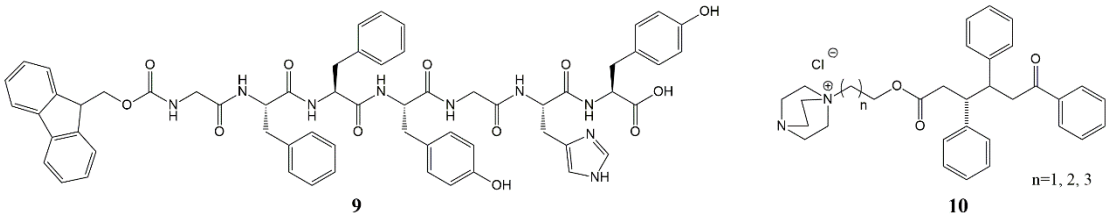
- the aqueous microenvironment provided by the hydrogel protects the enzyme from deactivation in the organic solvent, and
- facilitation of easy transport of product back to organic phase, reducing the inhibition of the catalyst embedded in large pores of the hydrogel.[112,113]

The overall nature of gels like rheology, chirality, morphology, and their basic chemical architecture has been found to affect their overall catalytic activity. Also, they offer an edge in terms of remarkable properties like high active surface area, highly solvated heterogeneous nature, great diffusion properties, easy preparation and most unique of all, stimuli-responsive reversible nature. No wonder, many organic transformation reactions such as photochemical reactions, Suzuki type couplings, aldol reactions, cycloaddition, metathesis and various types of polymerizations have been successfully attempted using molecular gels.

Escuder and coworkers are pioneers in the area of supramolecular catalysis and have reported various studies focused on organocatalysis. Supramolecular gels can be employed for catalytic purposes as they offer advantages of both, homogeneous and heterogeneous catalysts. In certain cases, the gel phase is reactive and can get transformed after the reaction, in others, the gel can showcase nearly ideal catalytic activity and get replenished after the reaction. It is believed that hydrogels self-assemble *via* hydrophobic interactions and organogels comprise of slightly hydrophilic interactions, which are responsible for their respective aggregation. These effects cause the emergence of catalytic properties as the hydrophobic pockets and van der Waals forces present in the hydrogels provide a reaction center for the starting ingredients.[114–116]

There have been several reports based on peptide hydrogels and their catalytic activity for carrying out a variety of reactions with decent selectivity and stereoselectivity. Reactions like asymmetric addition, Mannich reaction, click reaction, Heck reaction,

Diels-Alder, aldol and many others have already been successfully carried out using supramolecular gels.[117–119]



9 **10**

Scheme 1.4 Chemical structures of some catalytically active gels reported in literature

In a study, the authors attempted to grow an esterase-like **C**atalytically **A**ctive **S**upramolecular **H**ydrogel (CASH) in an open-cell polymer foam (Scheme 1.4, **9**). This material was found to be robust enough for use in continuous flow reactors, reusable and stable for months. The supported CASH also showed kinetic resolution capacity which allowed isolation of quantitative amounts of enantiopure carboxylic acids from racemic or enantio-enriched inactivated esters. This report confirms that a spatial control of peptide self-assembly from the surface of porous polymer materials leads to formation of nanofibrous networks which display attractive catalytic properties.[120]

In another study, oxotriphenylhexanoate containing moieties were developed for their catalytic activity in flow-type reactions (**10**). The catalytic gel was used to catalyze the Knoevenagel reaction with enhanced product formation, reusable up to five times.[121]

In an interesting report, Smith and coworkers studied the catalytic activity of Pd loaded self-assembled DBS-$CONHNH_2$/alginate gels. The gel could be extruded in the form of beads and worms and were treated with $PdCl_2$ solution. The gel samples could uptake the palladium(II) and efficiently reduce it to palladium(0), the active moiety for catalyzing standard Suzuki-Miyaura cross-coupling reaction. The reaction was carried out between 4-iodotoluene and phenylboronic acid with- and without-stirring the reaction vessel with an impressive yield of 98-99%. The authors reported that just a single bead could facilitate the reaction. Such a hybrid gel approach offers an edge over using polymeric gelators and can be very useful in designing LMOGs for extended applications.[122]

1.3.4.3 Sensing

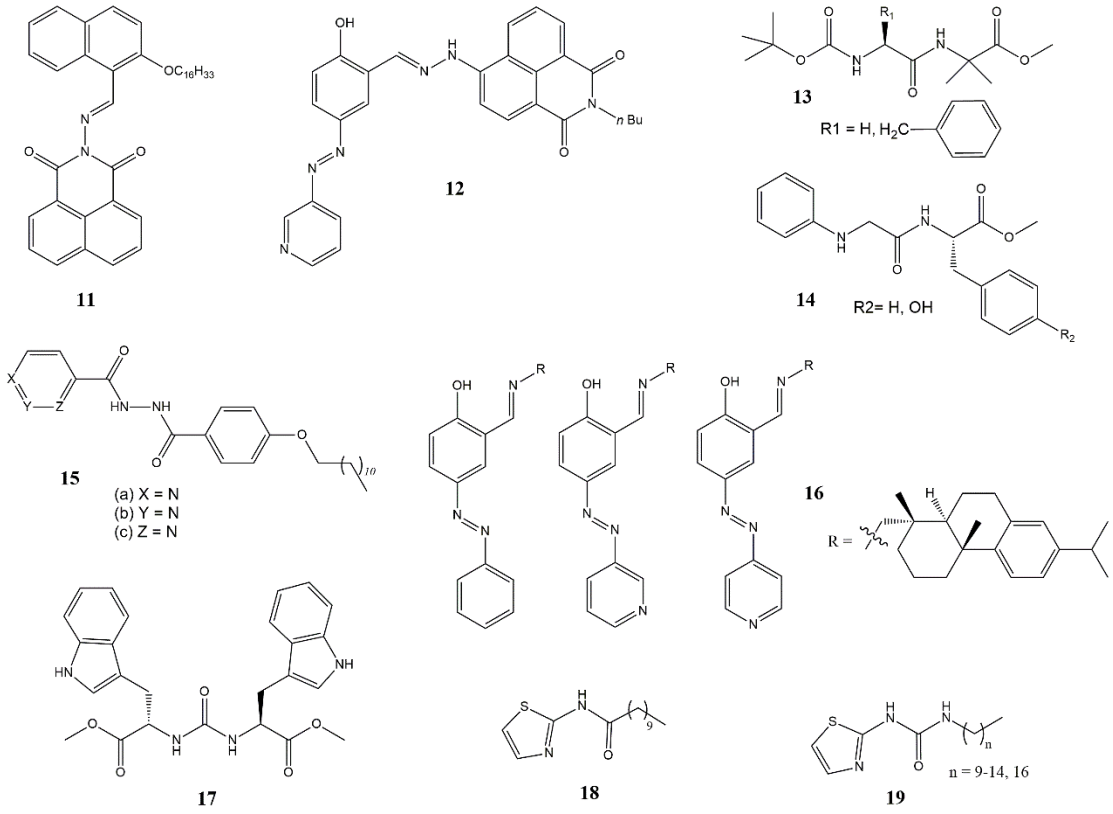
Gels have been widely used for sensing and binding with metal ions and anions. This involves interaction of externally added analytes with the gel networks which can produce visually detectable responses. Usually, such an interaction is followed by a gel-to-sol transition which may also serve as a 'chemical-switch', but in certain cases, a constructive interaction may cause alteration in the existing gel network resulting in 'gel-to-gel' transition.[123] The most studied is the fluoride ion sensing; by virtue of its high basicity, fluoride ion is expected to bind with even the weakest of acidic functionalities. Although it can also cause deprotonation in certain hydrogen-bonded self-assemblies. It is also known to act as a chemical switch because of its ability to bind with hydrogen-bonded moieties.[124] In certain studies, addition of specific anions caused gelation, whereas the molecules did not form gels in their own right.[125] This is termed as 'anion enhancement' and often follows the Hofmeister series[126] :

$$I^- < ClO_4^- < NO_3^- < Br^- < Cl^- < F^- < SO_4^{2-}$$

The ions to the right are more hydrated and referred to as kosmotropic ions, which cause 'salting out' or breaking of the gel; to the left are less hydrated, chaotropic ions which cause 'salting in' or gelation. The concept of synthesizing organic salts for exploring their gelation behavior is based on the same fundamental, keeping one moiety fixed and varying the other to obtain a combinatorial library and understand the plausible mechanism behind gelation behavior.

Cyanide ions demand attention in that regard as they happen to be one of the most threatening in biological systems. They combine with the active site of cytochrome-*c* oxidase causing disruption in the electron-transport chain from the central nervous system to the endocrine system. Discharged mainly as industrial waste, cyanide ions exhibit hypertoxic effects even at below micromolar concentrations; they are found in water bodies and get accumulated in the biosphere with every increasing level. To tackle this, gel-based sensors have been developed which can bind with and congeal the cyanide ions. Most of the reports focus on gelators which cause a phase transformation or a visible color change, when brought in contact with the analyte species. Even though, there are limited reports focusing on small molecule gelators which can specifically bind with and sequester cyanide ions from water bodies. Most of the reports feature studies carried out in pure systems, those gelators may or may not

work the same way in wastewater or sea contaminated with industrial effluents. This calls for development of improved systems capable of better absorption with enhanced physical properties.



Scheme 1.5 Chemical structures of gel-based sensing materials

Various reports on naphthalimide based gel-sensors with efficient binding and prominent photophysical properties are available in literature. The naphthalimide moiety is a chromophore which can exhibit great luminescence, photostability and a large Stokes' shift. Based on these facts, Wei and coworkers designed a molecule with 1,8-naphthalimide moiety which exhibited gelation behavior in DMSO and could selectively sense cyanide ions with ultrasensitive detection behavior (LOD= 1.82×10^{-10} M) (Scheme 1.5, **11**). The binding with cyanide ions was found to be coming from anion-π interactions between the CN^- ions and electron-deficient naphthalimide groups. The response mechanism was studied using various techniques and a change in fluorescence color was also observed during the period of detection.[127]

Ghosh and coworkers reported a molecule with similar backbone containing pyridyl-azo phenyl derivative which could gel DMSO:water (1:1, v/v) and exhibited gel-to-sol transition selectively in presence of cyanide ions (**12**). A similar compound with protected phenolic group did not show gelation. The gel of **12** was also found to be pH-sensitive because of the presence of -OH and -NH- groups; stable in a pH range of 2-8.5.[128] These types of systems provide an efficient way of designing ultrasensitive gel materials which can be visually used to detect hypertoxic ions.

Not only the cyanide ions but metals when present beyond permissible limits in water can cause dysfunctioning of multiple organs in the body and seriously endanger human health. For instance, long term accumulation of Cu^{2+} can cause Wilson's disease, Alzeimer's and irreversible liver and kidney damage. Other heavy metals like mercury, lead and cadmium can prove to be fatal and also cause severe kidney and brain damage. These ions can cross the placental barrier and even damage the vital organs of unborn fetus. Haldar and coworkers designed four dipeptide based gelators which selectively formed metallogels with copper, zinc and lead ions (**13, 14**).[129]

In a study published by Zhou and coworkers, a series of pyridine-hydrazide isomeric compounds was designed and synthesized which showed gelation behavior in a variety of solvents like alcohols, toluene, xylene, ACN, THF, etc. (**15**) The compounds were investigated for their anion responsive behavior and were found to selectively bind with fluoride ions. With metals, selective metallogelation was observed in presence of copper and ferric ions. A transformation of organogels to metallogels was observed and monitored using fluorescence spectral titration. According to a plausible mechanism proposed by the authors, the metal coordination with the N atom of pyridine group along with hydrogen bonding, π-π interactions and van der Waals interactions among the long aliphatic chains together promoted metallogelation.[130]

Recently, Ghosh and coworkers reported dehydroabietylamine linked Schiff bases which exhibited organogelation behavior (**16**). The theoretical studies highlighted different aggregation modes of the gelators. The compounds were found to be responsive to Cu^{2+}, Fe^{3+} and Hg^{2+} ions. A visible color change followed by a gel-to-sol transition on gradual addition of metal ions verified the responsive behavior of the compounds.[131] Such visual detection studies can help in development of real time sensors with impressive detection limits and removal efficiencies.

In a similar study by Wei and coworkers, rhodamine-based Schiff base was synthesized to act as supramolecular fluorescent material for detecting Cu^{2+} and Hg^{2+} ions. Rhodamine derivatives in spirocyclic form tend to be colorless and non-fluorescent, while a metal coordination causes spirolactam ring-opening and induces fluorescence in the system. Significant structural modifications can cause the system to selectively bind and sense specific metal ions.[132] These systems make candidates for development of smart sensors with ultrasensitive detection of metal ions. In an interesting study, pillar[*n*]arene-based supramolecular gel which was non-fluorescent in its own right served as a fluorescence 'turn-on' sensor to selectively sense dihydrogen phosphate ions, which was achieved by the signal amplification strategy caused by the introduction of metal ions into the supramolecular gel. The ultrasensitive mechanism gave an LOD value of 2.82 nM for Fe coordinated gel.[133]

In a study by Mohar and Das, a tryptophan based gelator *cum* sensor was developed for detection of iodide and fluoride ions (**17**). The compound acts as an optical cascade sensor and could be utilized to detect iodide ions present in aqueous media. The iodide bound compound could be then utilized to bind with fluoride ions. Initially, the iodide ions were bound to the indole N-H but free urea proton in the system allowed cascade sensing of fluoride ions as they are basic enough to bind with urea protons. The gel was formed in 1,2-dichlorobenzene and was further utilized to absorb various dyes from water. Interestingly, the gel showed significantly high selectivity towards adsorbing zwitter-ionic dyes over cationic, anionic and neutral dyes.[134]

Ballabh and coworkers reported a thiazole based gelator containing a long aliphatic chain which showed exceptional fluoride sensing abilities. Surprisingly, no gel-to-sol transition was observed on external addition of fluoride salt (**18**).[135] Recently, they reported thiazole-urea based compounds containing long aliphatic chains (**19**).[136] The compounds turned out to be excellent gelators for polar solvents. These compounds showcased a highly selective and sensitive detection of iodide ions followed by degelation of the acetonitrile gels upon external addition of iodide salt. Such studies can be very promising in designing smart-sensors with desired properties and applications.

1.3.4.4 Templates for nanoparticle synthesis

Supramolecular assemblies have an ability to create a variety of nano structures with desired shape, size, chemical composition, and function. From porous and chiral silica nanostructures to metallic nanoparticles, organogels are an efficient way to synthesize different classes of functionalized materials with desired morphologies like fibers, rods, tubes, ribbons, helices, intertwined double helices, spirals, vesicles and many more. Though there are many synthetic methods known for the preparation of nanostructured materials, the use of supramolecular assemblies remains a credible approach. In addition, semi-conductor materials have also been templated using gels. It is the difference of cohesive energy of the molecules between the dispersed state and aggregated state which favors the formation of 1D nanostructures. Moreover, the reversible nature of supramolecular gels along with their highly active surface area modulated by the self-assembled fibrils offer a favorable environment for the same. It is generally believed that such nanostructures obtained from organogels are fragile and more collapsible; hence, polymeric gelators are more commonly used as they can generate more robust and functional materials.[92,137–139]

The process of transcription generally occurs in steps; firstly, the gel template (organic moiety) is brought into contact with the inorganic precursor material in solution form. Then, in presence of a suitable catalyst, the inorganic material gets deposited on the inner or outer surface of the gel fibers. The template is usually removed by calcination to obtain pure inorganic material.[140,141] Gels based on peptides have attracted great attention for the preparation of composite or hybrid inorganic nanoparticles. This is because, the peptide gels provide colloidal stability to the nanoparticles and can also assist in controlled delivery. They provide a green route for synthesis and the obtained material can be utilized in biomedicine, catalysis, sensing, etc.[142] Moreover, chiral LMOGs derived from amino acids are known to self-assemble into helical fibers and twisted/coiled nanoribbons by hydrogen bonding and π–π interactions. These LMOGs have been employed to create silica nanotubes with single-handed helices, where molecular-scale chirality exists at the inner surfaces. Such systems can be efficiently used to prepare optically active helical nanostructures.[143]

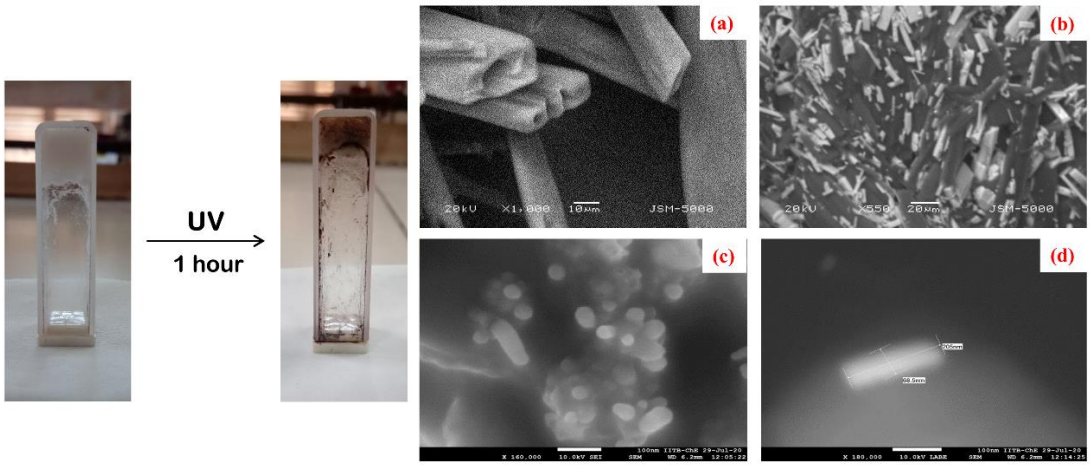


Figure 1.15 UV irradiation of gel containing silver salt; (a) SEM of hollow tubes found the fibers of organic salt based gel; (b) SEM image of organogel containing Ag NPs (after irradiation); (c), (d) SEM of calcined and isolated Ag NPs.

In a unique study, Ballabh and coworkers reported a series of thiazole-based amides containing long aliphatic chains which displayed odd-even effect in terms of gelation behavior. The compounds containing even number of methylene groups turned out to be better gelators in terms of number of solvents gelled, mgc values and stability than those with odd number of -CH_2 groups. They further used these gels to prepare Ag and ZnO nanoparticles by template-directed method. Astonishingly, they found that size of the nanoparticles increased with increase in aliphatic chain length of the gelators. This behavior was attributed to an increase in the voids between the 3D networks of the gel fibers.[144] This result highlights the correlation between the gelator complexity and the pore size between the gel fibers, in this case, probably due to elevated van der Waals interactions and interdigitation between the aliphatic chains. The same group later reported a series of pivalic acid based two-component gelators. One of these compounds displayed hollow tubular architecture in its network (Figure 1.15 (a)). This gelator was further employed for the preparation of silver nanoparticles which possessed a rod-shaped morphology. A simple synthetic procedure of UV irradiation of the mixture of gel and silver salt solution led to the formation of monodispersed silver NPs of size approx. 38 nm with a face centered cubic structure. Mainly, the enhanced electrostatic interactions in the gelators fibers provided an added stability to the NPs and governed their unique morphology.[53]

In an interesting study, the authors reported that a cocktail of chiral gelator, a polyoxometalate and a silver salt when heated to elevated temperature and eventually cooled, led to the formation of gel precursor. Microscopic studies revealed that right-handed ribbons with respect to those present in neat gel fibers were formed by rapid cooling treatment, and left-handed ribbons were formed by slow cooling treatment of the gels. The polyoxometalate was used to catalyze the conversion of Ag^{+} to Ag^{0} under the UV treatment.[145] This was a unique study which highlighted a method to control the chiral arrangement of the Ag NPs in the gel matrix.

1.3.4.5 Biomaterials

The dynamic nature of molecular gels allows them to better interact and adapt to their environment, including human body.[146] Gels find a plethora of applications in biomaterial devices like blood glucose monitoring, sensors for electrolytes and drugs, healable coatings, tissue engineering, artificial muscles and tendons, etc. and have established themselves in the area of regenerative medicine.[91,147–150] Gels derived from biocompatible sources like amino acids, cellulose, etc. can be very efficient in developing novel biomaterials. Smart drug-delivery systems have been proposed, where the gels are engineered according to their response towards external stimuli such as temperature, pH, etc. for targeted release of drug.

In that regard, supramolecular fluorescent gels find a variety of applications in cell imaging, disease diagnosing, biological sensing and real time detection, as a response to enzyme-triggers, metal-ligand coordination, hydrogen bonding and even host-guest interactions.[151] However, their *in vivo* applications are limited; as once injected/implanted in the body, their mechanical properties are likely to change. To overcome this aspect, certain biocompatible systems have been proposed, which possess a potential to form defect-free, tough gels that can sustain the hostile environment in the body. This can be best explained by the fact that hydrogels are generally regarded as biocompatible materials. They have a porous structure which holds a large volume of water and hence, are best suited to accommodate water-soluble drug molecules.

Gel is conventionally formed by heating, change in pH or enzymatic action; it can be then simply applied at the site or injected, and it is the degradation of gel that releases the bound drug to act at the target site. In certain cases, drugs are incorporated in supramolecular assemblies along with a functional moiety, so that a self-assembled system when ingested and made to come in contact with enzymes, can trigger the drug release on targeted sites. This enzymatic cleavage can be useful in either releasing the drug from a prodrug amphiphile or simply to break the self-assembly for its release and fast action. Another way is to encapsulate a poorly soluble drug in a gel pocket, which on being triggered by the presence of enzymes in the body, can be released followed by gel degradation.[152,153] Many commonly used drugs have been modified following the principles of supramolecular chemistry to form mainly hydrogels, which find applications in enhanced drug release. These drugs include vancomycin, 6-aminoquinoline, ibuprofen, naproxen, flurbiprofen, etc.[154]

Widely used anti-cancer drugs like *cis*-platin, paclitaxel (a highly insoluble, hydrophobic, anti-cancer drug), etc. have also been formulated using stimuli-induced molecular gels, which are designed to modulate the release rates over prolonged periods without compromising their biological activities.[155] Another very fascinating area in biomedical applications is generation of 3D cell cultures. However, the research largely relies on the data obtained from 2D cell culture studies and the behavior of tissues is very different in the two situations, but since molecular gels can be used to create 3D cell culture models, we can expect to gain more insights in the area with upcoming reports. 3D printing is typically a property of gels which can form spherical domains containing tightly packed fibrils. Such gels can be 3D printed into an array of layered designs depending on the application desired.[146,156]

There are various examples where peptide based self-assembling systems were used as delivery vehicles for targeting various diseases in the body. It is believed that bioactive peptide gels have the potential to address the challenges linked to oral drug delivery owing to their ease of synthesis, biocompatibility, biodegradability, and non-toxic nature. They have been utilized in the treatment of heart failure, cell culture and tissue engineering, anti-tumor therapy, designing new antibiotics, vaccine adjuvants and many more. They have been used as drug delivery vehicles for diseases targeting the colon and gastrointestinal tract. They can be molded into nanospheres, beads or any

desirable shapes for efficient drug delivery directly at the site. There has been a lot of research lately to reduce the adverse effects of non-steroidal anti-inflammatory drugs (NSAIDs). These drugs when taken in large amounts can irreversibly damage liver, kidney, and other vital organs of the body. In this respect, various groups have attempted to design NSAID-peptide prodrug conjugates which have the ability to form hydrogels. This allows hydrogel 'self-delivery' and a selective COX-2 inhibition over COX-1 inhibition, thereby retaining the anti-inflammatory benefits of the drugs and minimizing gastric side-effects. These 'on demand' drug delivery systems are likely to have enormous impacts on treatment of a variety of diseases.[157,158]

Dastidar and Parveen synthesized a series of PAM (primary ammonium monocarboxylate) salts to gain access to a well-known NSAID ibuprofen with various biogenic amines. A supramolecular synthon approach was followed with the idea that supramolecular synthons that converged into 1D/2D assemblies predictably induced gelation. Likewise, most of the salts synthesized in this series turned out be gelators and could be successfully utilized for *in vivo* anti-inflammatory purposes.[159] A similar study for the treatment of inflammatory diseases was reported by Limon and coworkers. Curcumin and its derivatives hold a strong therapeutic potential for treating skin inflammation, for e.g., in psoriasis or post radiotherapy. However, the potential benefits of curcuminoids are limited because of their low oral bioavailability. To tackle this, curcumin incorporated supramolecular gels were prepared and exploited for dermal applications, which allowed on-site application allowing transdermal permeation and systemic absorption of the curcuminoids.[160]

Sullan and coworkers reported a novel peptide amphiphile which formed hydrogel at very low mgc values, possessing a nanofiber matrix morphology, composed of β-sheet aggregates. This gel was then explored to generate a library of multi-component systems with the potential to mimic the complex natural extracellular matrix. The resulting gels displayed tunable stiffness, self-healing abilities, diverse morphologies and exceptional biocompatibility with the mesenchymal stem cells.[161] Such systems can be tailored for more specific applications and hold the potential for developing efficient biomaterials.

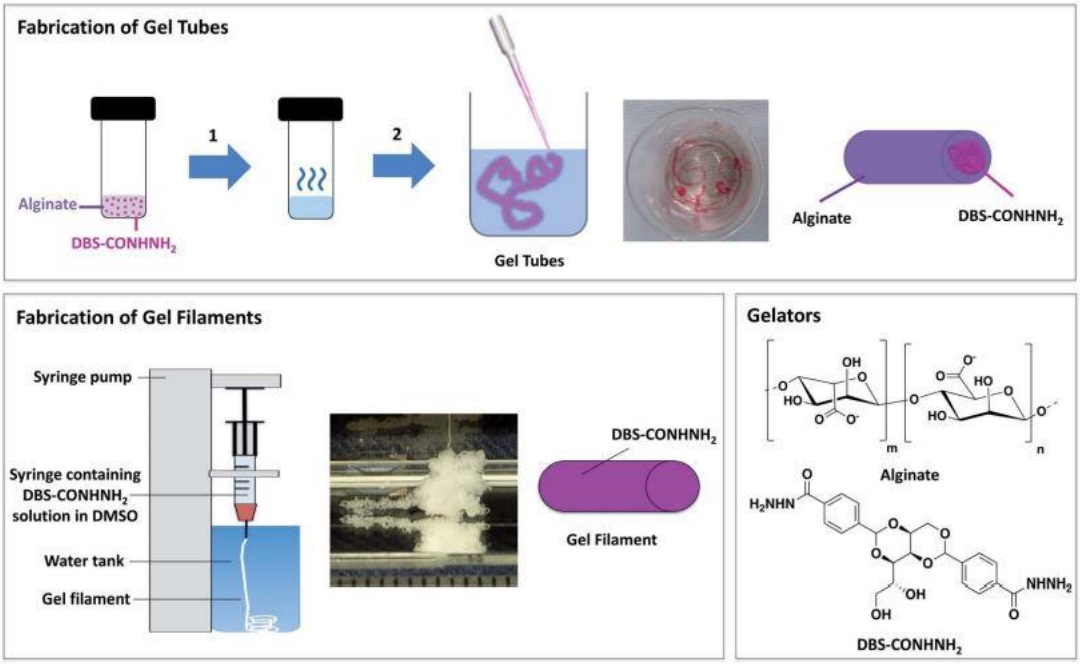


Figure 1.16 Fabrication of DBS-CONHNH2/alginate core–shell gel tubes reported by Smith and coworkers. Adapted from ref. [162] **Copyright 2022 Royal Society of Chemistry**

Smith and coworkers have been pioneers in developing self-assembled gels for development of biomaterials. They reported a low molecular weight gelator based on DBS-CONHNH$_2$ (dibenzylidene sorbitol derivative) and a natural polysaccharide, calcium alginate which self-assembled into microgel beads, an extremely rare phenomenon for gelation systems. The beads remained stable in water for several months and could survive injection through a syringe. These beads were employed to deliver heparin, a bioactive molecule capable of cell proliferation. These microgel beads were loaded with heparin and its controlled release was monitored along with the stability of gel beads. The beads could successfully encapsulate and release the drug molecules which positively influenced the growth of human stem cells.

They published another study where they employed a similar gelation system to form a dual network hybrid hydrogel containing either glucono-δ-lactone (to lower the pH) or diphenyliodonium nitrate (as a photoacid to lower the pH) for enhancing stem cell growth. These gels could promote *in situ* formation of silver nanoparticles by reduction of Ag(I) to Ag(0), when exposed to silver salt solutions. Further, it was found that these AgNPs-loaded hybrid hydrogel beads were active against drug-resistant bacteria at high Ag loadings and had a potential to be used as antibacterial biomaterials. The same gel assembly was employed for creating gel tubes which allowed *in situ* formation of gold

nanoparticles to promote bone growth by facilitating osteogenic differentiation and hence, finds applications in bone tissue engineering (Figure 1.16). In another study, they combined DBS-$CONHNH_2$, which allowed pH-mediated controlled release of an API, with another gelator, MBS-CO_2Me (2,4-monobenzylidene sorbitol derivative) which introduced mechanical strength in the gel assembly. This gel was employed for controlled release of naproxen, an anti-inflammatory drug used to relieve symptoms of various forms of arthritis. The hybrid gel was found to facilitate pH mediated controlled release of the drug in small intestine.[162–165]

In an interesting study, Sun and coworkers demonstrated stimuli responsive drug release by using a tetrapeptide as a self-assembling backbone with switching function. The pH-triggered hydrogel so formed exhibited optimized release effect of etoposide, an anti-cancer drug, as compared with the free drug that suffers from shortcomings like drug burst release, short plasma circulation time, etc. Such systems based on nano-carriers can significantly enhance the efficiency of anti-cancer drugs with improved permeability and retention effect.[166]

In another study, bola-amphiphiles based self-assemblies were exploited for inducing cancer cell apoptosis *via* membrane effect.[167] Such systems open new perspectives in rational design of biomaterials with promising therapeutic abilities.

1.3.4.6 Oil spill remediation and pollutant removal

Oil spill refers to accidental discharge of crude oil in the marine environment as a result of natural or anthropogenic activities. The major constituents are the hydrocarbons, which are largely immiscible with water and as a result of weathering processes, can convert into highly viscous oil slicks which are far more difficult to treat. Moreover, various non-biodegradable pollutants don the marine systems by virtue of similar anthropogenic activities. They thrive and prevail in the environment and get accumulated in the marine ecosystem. They can even find their way back in our diet and pose serious health problems. Traditional methods like sedimentation, flocculation, photocatalysis, etc. have been employed for pollutant uptake, but we are still far from achieving an ideal treatment strategy.[168] Molecular gels find essential applications in containing oil spills and sequestration of pollutants from aqueous medium. They have the ability to selectively congeal the oil phase (also called Phase Selective Organo-

Gelation, PSOG, Figure 1.17) which can be skimmed off the surface of water and simply heated to retrieve back the oil. This strategy causes maximum amount of oil to be gelled and hence, recovered.

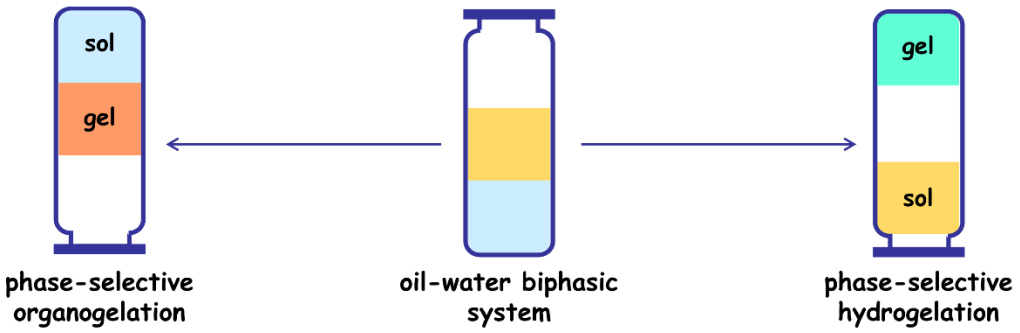


Figure 1.17 Graphic illustrating two types of phase selective gelation

Generally, phase selective gelation refers to selective gelation of one phase in an immiscible mixture. While most of the reports are mainly focused on phase selective organogelation, recently Raghavan and coworkers reported phase selective hydrogelation of laponite nanoparticles in presence of an organic acid. In a first, they demonstrated hydrogelation in presence of immiscible organic solvents activated by the self-assembly of laponite nanoparticles into a three-dimensional 'house of cards' network; where the activation of nanoparticle assembly occurs through the organic acid dissolved in adjacent organic phase without any hardcore organic synthesis.[169]

An ideal PSOG should be essentially immiscible in the aqueous phase, so the molecules can invariably interact with the oil phase *via* non-covalent interactions and immobilize it at ambient temperature, when added in powdered form in order to minimize the disadvantages of using a carrier-solvent based gelator. It should be essentially non-toxic and be able to form mechanically robust gels in the hostile marine environment without partitioning into water and adversely affecting the marine flora and fauna.[170–174]

A similar strategy can also be applied for sequestration of pollutants like metal ions, dissolved dyes, pharmaceuticals, and other organic contaminants from sea water. Heavy metal ions and anions like arsenates, perchlorates, phosphates, nitrates, etc. are discharged in water through industrial activities and cause toxicity or eutrophication when present in large amounts.

Compounds which can form *in situ* hydrogels in presence of these ions can be employed to efficiently uptake these ions. As compared to cations, anions often display better binding ability as they have larger range of protonation equilibria, smaller charge-to-size ratios, and no coordination preferences as in metal ions. Hence, the gels employed need to be designed with principles of ionic recognition, host-guest interactions and Hofmeister series[126] to preferentially remove the target pollutant ionic species.

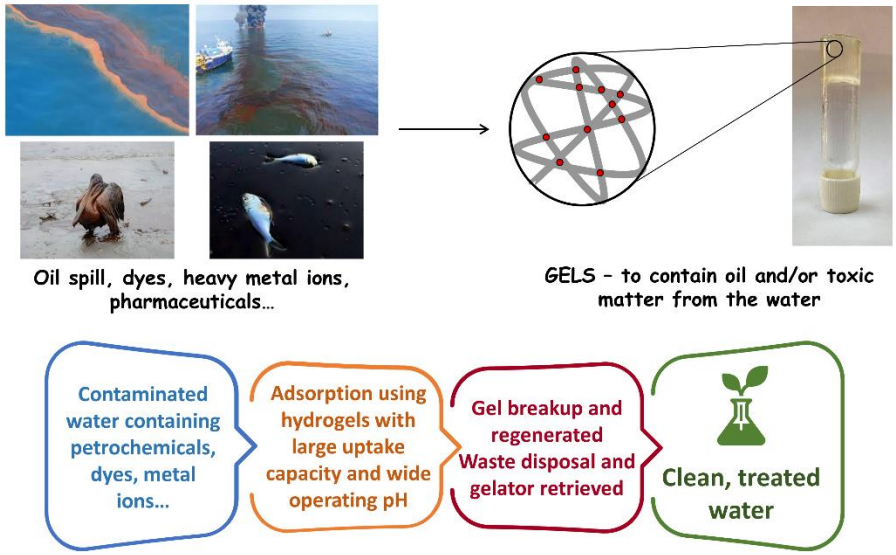


Figure 1.18 An illustration and schematic demonstrating uptake of heavy metals, ions and dyes using molecular gels

Dyes are a class of synthetic organic compounds which are discharged as effluents and remain highly persistent in the environment. They are highly conjugated systems that can be non-biodegradable, potentially toxic and even carcinogenic in nature. Not only this, their highly intense colors make it difficult for the visible light to penetrate the water surface and hamper the aquatic photosynthetic efficiency of the system. Similarly, pharmaceuticals and organic wastes find their way in water and pollute the marine environment, not to forget their harmful effects on the aquatic life.

Hydrogels employed for removal of such pollutants involve selective interaction of the gel fibers and target compounds *via* specific intermolecular interactions which causes uptake of such species thereby reducing their concentration in water (Figure 1.18). Hydrogels can absorb these pollutants in their three dimensional, highly porous network. Moreover, they can be designed with desired specificity for certain species,

high adsorption capacities and efficiencies (Figure 1.19). There are various reports of biodegradable and hence, biocompatible and non-toxic systems which have been successfully employed for the said purpose.[175]

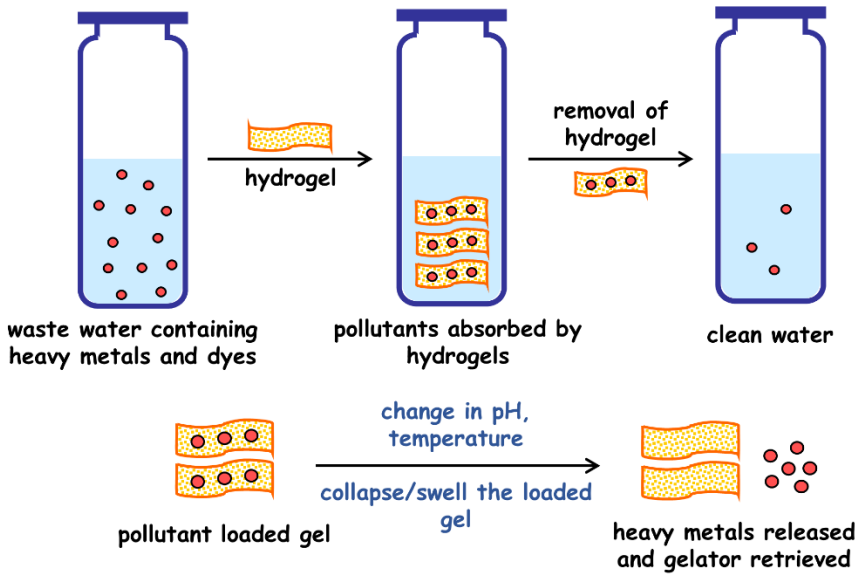
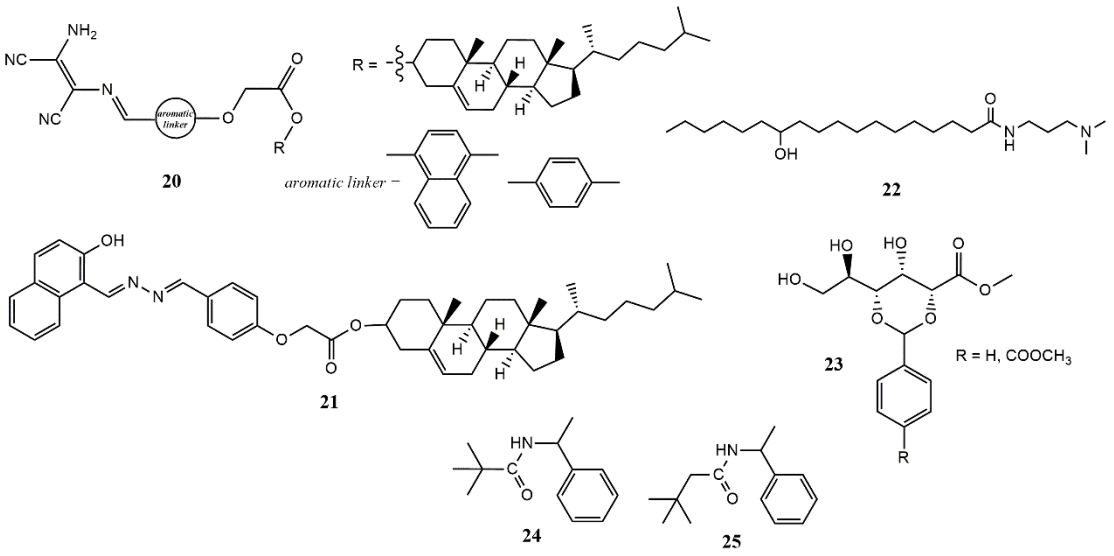


Figure 1.19 Hydrogels for tackling water pollution

The first report of phase selective organogelation was made in 2001 when a simple amino acid derivative, N-lauroyl-L-alanine was found to selectively congeal oil in presence of water. It was considered unique as the idea of one solvent being gelled in presence of another was not a commonly observed phenomenon.[176] Since then, various monographs have been published on phase selective organo-gelation to tackle marine oil spills.

Much research has been focused on developing easily available, inexpensive, biocompatible and biodegradable organo-gelators which are environment friendly and do not contaminate the oil phase at the same time. Their well-defined chirality and origin from non-toxic natural resources make them attractive candidates for design of organo-gelators. This led to the development of various types of sugar-based gelators[48] which could efficiently congeal petrochemicals and also facilitated their easy recovery.[49,177–179] Several amino acid based phase-selective organogelators have also been developed for oil spill recovery.[180–182] Other systems like chalcone derivatives[183],

dehydroabietic acid[184], triphenylphosphonium functionality[185], etc. have also been explored.



Scheme 1.6 Chemical structures of some recently reported phase-selective organo-gelators

In a study by Ghosh and coworkers, diaminomalenonitrile functionalized organo-gelators containing an aromatic linker and a cholesterol backbone were reported to function as selective gelators of oil in biphasic mixtures (Scheme 1.6, **20**). The authors reported self-healing and injectable behavior of the compounds along with selective visual sensing of fluoride and cyanide ions. This exceptional sensing ability was dedicated to the presence of diaminomalenonitrile moiety. The gels also served as cleaning agents by sequestering dyes from aqueous solutions. Crystal violet, malachite green and uranine were chosen for the study, out of which the former two gave impressive removal efficiencies within a minute.[186] The same group designed a molecule with diazine and phenol functionalities along with a cholesterol backbone (**21**) with a gelation potential for hydrocarbons and fuel oils. The molecule also served as sensor for cyanide ions showing a gel-to-sol phase transformation followed by changes in color and fluorescence of the system. The selective sensing was found to be a consequence of deprotonation of the naphthol -OH in presence of cyanide ions. Dye adsorption studies showed promising results with crystal violet and malachite green, showing removal efficiencies upto 99%.[60]

In an interesting study by Lu and coworkers, an amide of 12-HSA and 3,3-dimethylaminopropylamine (**22**) was reported to congeal several organic solvents and fuel oils at low concentrations. The amide moiety could induce strong hydrogen-bonding interactions and the *tert*-amine group could be utilized for pH-responsive behavior. This caused the molecule to reversibly switch between hydrophobic and hydrophilic behavior; the sol-to-gel and gel-to-sol transition could be triggered just by regulating the pH of the system at room temperature, separating the recovered oil and the gelator. This responsiveness was attributed to the protonation and deprotonation of *tert*-amine moiety. At acidic pH, the protonation of amine group caused breakdown of the gel network and as the pH was raised to alkaline, the gel was re-formed as all the deprotonated amide molecules shifted back to organic phase.[187] Fang and coworkers synthesized D-gluconic acetal based organo-gelators (**23**) which displayed phase selective gelation in aromatic solvents like toluene, xylenes, benzene, etc. in presence of biphasic systems.[188]

In a similar study, Ballabh and coworkers reported a series of amide based organogelators based containing a *tert*-butyl moiety, capable of congealing alkane homologues and petroleum products (**24,25**). These compounds are some of the smallest known systems capable of exhibiting PSOG in biphasic systems. The compounds were designed with a strategy of incorporating three aspects:

- a structural moiety which can promote van der Waals/π-π interactions (long-chain aliphatic/ aromatic compounds),
- a directional hydrogen bonding linker (amide) and
- a bulky end group (*tert*-butyl).

Both the aliphatic as well as aromatic structural units were incorporated along with the bulky functional group on one side of the molecules to induce the synergistic effect of long-chain interdigitation/ π-π interactions, which would bring stability to the overall supramolecular assemblies formed by 1-D hydrogen bonding of amide functionality, and the presence of sterically hindered *tert*-butyl group would avert very close packing among the neighboring molecules. Also, the amide group incorporated in all the molecules acted as a linker which could form 0-D or 1-D supramolecular synthon, causing gelation. Six compounds were reported for displaying gelation behavior in diesel, silicone oil, cooking oil and *n*-alkanes (*n*=6-16) using a conventional heat-cool

cycle, ultrasound and even strong sunlight. These compounds were also utilized for successful absorption of methylene blue and rhodamine B dyes in biphasic systems.[189]

In a study by Li and coworkers, dye removal studies were performed using an azobenzene based phenyl alanine derivative. The molecule could gel polar solvents at low concentrations and displayed good adsorption capacity for methylene blue and rhodamine B dyes in a pH range of 6-9. The adsorption followed Langmuir isotherm model and displayed pseudo second-order kinetics.[190]

Steed and coworkers reported carbohydrate-based supramolecular gels which could selectively adsorb chromium(VI) from aqueous phase at neutral pH. They also reported a gelator containing saccharate ion which could facilitate chemisorption of the chromium species followed by their conversion into chromium(III) species which are potentially less toxic.[191]

There has been an enormous growth in the reports of soft materials with environmental applications. These systems can undoubtedly be utilized in tackling many such issues we are facing today. Essentially, such systems are considered more credible if derived from sustainable sources which make them biocompatible and environmentally benign. We hope to see more of such reports with better activity and efficiency in the near future.

1.3.5 Challenges and futuristic aspects

In summary, the interest in potential applications and the unique properties of self-assembled systems has experienced a massive surge in the last few decades. Various techniques employed to study the sol-gel transitions, visualizing the gel network in native form, predictive models obtained from computational calculations, single crystal studies, etc. have improved our understanding of these conspicuous, yet mysterious systems. This chapter is an effort to highlight the progress made in the area of supramolecular gelation systems in the last 4-5 years and yet touches nothing but the tip of the iceberg. With every passing day, we make progress in understanding these systems better, paving our way towards more advanced applications with great potential for commercialization. Even though, there are many aspects untouched and many applications yet unexplored. Our fascination for pre-designed molecular gelators or devising predictive models which can identify gelators/non-gelators *prima facie* still remains a challenge. We expect to see better systems, designing paradigms and impressive applications in the near future with a hope to make the best out of these beautiful soft materials.

1.4 AIM AND OUTLINE

To exploit the presence of weak and highly directional non-covalent interactions such as hydrogen bonding, π-π, C-H…π interactions, etc. and relatively stronger and not-so-directional interactions such as electrostatic interactions to generate interesting supramolecular architectures and establish their role in the modification of drug formulations and governing supramolecular gelation/non-gelation behavior by investigating structure–property relationship; to investigate the applications of supramolecular gels in generating inorganic nanostructures, oil spill remediation, dye uptake, heavy metal sensing, etc.

Chapter 1 deals with the introduction of supramolecular chemistry, crystal engineering, role of non-covalent interactions, Hirshfeld surfaces and classification and characterization of Low Molecular mass Organo-Gelators (LMOGs). The role of solvent parameters in controlling gelation behavior is discussed. The chapter focusses on the recent advancements made in the area of supramolecular gelation in the last five years.

Chapter 2 discusses the synthesis and characterization of memantine (MEM) based salts using a combinatorial library approach. Various mono-, di- and tri-carboxylic acids with aliphatic and aromatic backbones were employed in the study. The salts synthesized were explored for their propensity to form various supramolecular synthons, as primary ammonium monocarboxylate (PAM) which can be easily extended to 2D by the presence of additional carboxylic acid functionality. A comparative study of weak non-covalent interactions in the parent compound MEM.HCl and newly synthesized salts of memantine was carried out in order to attain better understanding of the trends obtained from the dissolution studies.

Chapter 3A deals the synthesis of organic salts based on pivalic acid and primary amines (with aliphatic, alicyclic, and aromatic backbones). 10 out of 13 salts turned out to be organogelators. Single crystal studies were carried out to understand the hydrogen bonding patterns and to probe the mechanism of supramolecular gelation/non-gelation from crystal engineering approach. The role of solvent parameters such as dielectric constant, Hildebrand parameter, Hansen parameters, Kamlet-Taft parameters, etc. was also investigated in driving the gelation behavior. One of the gelators displayed well-defined rectangular pores in its fibers, which was utilized to serve as template for the

synthesis of silver nanoparticles.

Chapter 3B discusses the synthesis and characterization of *tert*-butylacetic acid based salts with the same set of primary amines as in Chapter 3A. All the salts were tested for their gelation behavior in various types of solvents. The behavior of pivalic acid based salts and *tert*-butylacetic acid based salts to form gels was assessed to identify better class of gelators and probable driving forces behind causing gelation.

Chapter 4A describes the syntheses and characterization of pivalamide based compounds having 3 parts - 1. structural moiety which can promote van der Waals/π-π interactions (long-chain aliphatic/ aromatic compounds), 2. directional hydrogen bonding linker (amide) and 3. bulky end group (*tert*-butyl). Six new gelators were discovered which could congeal alkane homologues (n>5 carbon atoms), diesel, engine oil, silicone oil, cooking oil, etc. under the effect of strong sunlight, UV light and ultrasonication. These compounds were tested for their ability to selectively congeal oil from oil-water systems at room temperature, in various forms (powder as well in solution form using various solvents). They were also employed for removing dyes present in aqueous solutions, which can contribute to tackle water pollution.

Chapter 4B deals with syntheses and characterization of *tert*-butylacetic acid based amides, using the same set of amines as in Chapter 4A. Their gelation abilities were compared with those of the compounds prepared in Chapter 4A. These compounds were explored for their phase selective organo-gelation behavior, dye removal and heavy metal sensing studies.

Chapter 5 describes synthesis of pivalic acid-based amides containing heterocyclic (thiazole and imidazole based) backbones. These compounds were utilized for the synthesis of mononuclear copper metal complexes. They were characterized using single crystal X-ray studies, Hirshfeld surface analysis, computational studies, ESI-mass spectrometry, UV-vis and ESR spectroscopy. These complexes were also exploited for their antioxidant activity, DNA cleavage, BSA binding and DNA binding abilities.

REFERENCES

1. Lehn, J.-M. *Supramolecular Chemistry*. (VCH Weinheim, 1995).
2. Cragg, P. J. *Supramolecular Chemistry*. (Springer Science+Business Media B.V., 2010).
3. Desiraju, G. R. *Crystal Engineering. The Design of Organic Solids*. (Elsevier, Amsterdam, 1989).
4. Desiraju, G. R. Chemistry beyond the molecule. *Nature* **412**, 397–400 (2001).
5. Nangia, A. K. & Desiraju, G. R. Crystal Engineering: An Outlook for the Future. *Angew. Chemie Int. Ed.* **58**, 4100–4107 (2019).
6. Desiraju, G. R. Crystal Engineering : A Holistic View. *Angew. Chem. Int. Ed.* **46**, 8342–8356 (2007).
7. Biradha, K., Su, C.-Y. & Vittal, J. J. Recent Developments in Crystal Engineering. *Cryst. Growth Des.* **11**, 875–886 (2011).
8. Desiraju, G. R. Designer crystals: intermolecular interactions, network structures and supramolecular synthons. *Chem. Commun.* **27**, 1475–1482 (1997).
9. Desiraju, G. R. Crystal engineering: From molecule to crystal. *J. Am. Chem. Soc.* **135**, 9952–9967 (2013).
10. Desiraju, G. R. *Crystal engineering: The Design of Organic Solids*. (Elsevier Science, 1989).
11. Krishnamohan Sharma, C. V. Designing advanced materials as simple as assembling Lego® blocks! *J. Chem. Educ.* **78**, 617–622 (2001).
12. Desiraju, G. R. Crystal engineering. From molecules to materials. *J. Mol. Struct.* **656**, 5–15 (2003).
13. Corpinot, M. K. & Bučar, D.-K. A Practical Guide to the Design of Molecular Crystals. *Cryst. Growth Des.* **19**, 1426–1453 (2019).
14. Steed, J. W. 21st century developments in the understanding and control of molecular solids. *Chem. Commun.* **54**, 13175–13182 (2018).
15. Braga, D. Crystal engineering, Where from? Where to? *Chem. Commun.* 2751–2754 (2003).
16. Price, S. L. Predicting crystal structures of organic compounds. *Chem. Soc. Rev.* **43**, 2098–2111 (2014).
17. Ghosh, S. & Mishra, M. K. Elastic Molecular Crystals: From Serendipity to Design to Applications. *Cryst. Growth Des.* **21**, 2566–2580 (2021).
18. Desiraju, G. R. Hydrogen bridges in crystal engineering: Interactions without borders. *Acc. Chem. Res.* **35**, 565–573 (2002).
19. Desiraju, G. R. Reflections on the hydrogen bond in crystal engineering. *Cryst. Growth Des.* **11**, 896–898 (2011).
20. Wang, H., Wang, W. & Jin, W. J. σ-Hole Bond vs π-Hole Bond: A Comparison Based on Halogen Bond. *Chem. Rev.* **116**, 5072–5104 (2016).
21. Desiraju, G. R. Supramolecular Synthons in Crystal Engineering—A New Organic Synthesis. *Angewandte Chemie International Edition in English* vol. 34 2311–2327 at 10.1002/anie.199523111 (1995).
22. Mukherjee, A. Building upon supramolecular synthons: Some aspects of crystal engineering. *Cryst. Growth Des.* **15**, 3076–3085 (2015).
23. McKinnon, J. J., Mitchell, A. S. & Spackman, M. A. Hirshfeld surfaces: A new tool for visualising and exploring molecular crystals. *Chem. Eur. J.* **4**, 2136–2141 (1998).
24. Spackman, M. A. & Byrom, P. G. A novel definition of a molecule in a crystal. *Chem. Phys. Lett.* **267**, 215–220 (1997).

25. Spackman, M. A. & Jayatilaka, D. Hirshfeld surface analysis. *CrystEngComm* **11**, 19–32 (2009).
26. Wolff, S. K., Grimwood, D. J., McKinnon, J. J., Turner, M. J., Jayatilaka, D. & Spackman, M. A. CrystalExplorer (Version 3.1). *University of Western Australia, Perth* (2012).
27. Turner, M. J., Grabowsky, S., Jayatilaka, D. & Spackman, M. A. Accurate and efficient model energies for exploring intermolecular interactions in molecular crystals. *J. Phys. Chem. Lett.* **5**, 4249–4255 (2014).
28. Turner, M. J., Thomas, S. P., Shi, M. W., Jayatilaka, D. & Spackman, M. A. Energy frameworks: Insights into interaction anisotropy and the mechanical properties of molecular crystals. *Chem. Commun.* **51**, 3735–3738 (2015).
29. Lloyd, D. J. *Colloid Chemistry, Vol. 1*. (The Chemical Catalog Co., New York, 1926).
30. Ferry, J. D. *Viscoelastic Properties of Polymers*. (Wiley, New York, 1961).
31. Zweep, N. & van Esch, J. H. Chapter 1. The Design of Molecular Gelators. in *Functional Molecular Gels* (eds. Escuder, B. & Miravet, J. F.) 1–29 (The Royal Society of Chemistry, 2014).
32. *Molecular Gels. Materials with Self-Assembled Fibrillar Networks (Eds. R. G. Weiss, P. Terech)*. (Springer, Dordrecht, 2006).
33. van Esch, J. H. & Feringa, B. L. New Functional Materials Based on Self-Assembling Organogels: From Serendipity towards Design. *Angew. Chem. Int. Ed.* **39**, 2263–2266 (2000).
34. Draper, E. R. & Adams, D. J. Low-Molecular-Weight Gels: The State of the Art. *Chem* **3**, 390–410 (2017).
35. Chivers, P. R. A. & Smith, D. K. Shaping and structuring supramolecular gels. *Nat. Rev. Mater.* **4**, 463–478 (2019).
36. Adams, D. J. Personal Perspective on Understanding Low Molecular Weight Gels. *J. Am. Chem. Soc.* **144**, 11047–11053 (2022).
37. Weiss, R. G. The Past, Present, and Future of Molecular Gels. What Is the Status of the Field, and Where Is It Going? (2014).
38. Rohner, S. S., Ruiz-Olles, J. & Smith, D. K. Speed versus stability – structure–activity effect on the assembly of two-component gels. *RSC Adv.* **5**, 27190–27196 (2015).
39. Sangeetha, N. M. & Maitra, U. Supramolecular gels : Functions and uses. *Chem. Soc. Rev.* **34**, 821–836 (2005).
40. Weiss, R. G. Chapter 1: Introduction: An Overview of the 'What' and 'Why' of Molecular Gels. in *Molecular Gels: Structure and Dynamics* (ed. Weiss, R. G.) 1–27 (The Royal Society of Chemistry, 2018).
41. Smith, D. K. Self-Assembling Fibrillar Networks — Supramolecular Gels. in *Supramolecular Chemistry: From Molecules to Nanomaterials* (eds. Steed, J. W. & Gale, P. A.) 3355–3376 (John Wiley & Sons, Ltd., 2012).
42. Mahinroosta, M., Jomeh Farsangi, Z., Allahverdi, A. & Shakoori, Z. Hydrogels as intelligent materials: A brief review of synthesis, properties and applications. *Mater. Today Chem.* **8**, 42–55 (2018).
43. Chang, H., Li, C., Huang, R., Su, R., Qi, W. & He, Z. Amphiphilic hydrogels for biomedical applications. *J. Mater. Chem. B* **7**, 2899–2910 (2019).
44. Lin, Y.-C., Kachar, B. & Weiss, R. G. Novel Family of Gelators of Organic Fluids and the Structure of Their Gels. *J. Am. Chem. Soc.* **111**, 5542–5551 (1989).
45. Weiss, R. G. A Very Personal View of Molecular Organogels. Examples Showing the Conceptual Links with Structurally Simple Gelators. *Macromol. Symp.* **385**, 1–5 (2019).
46. Zhang, M. & Weiss, R. G. Self-Assembled Networks and Molecular Gels Derived from

Long-Chain, Naturally-Occurring Fatty Acids. *J. Braz. Chem. Soc.* **27**, 239–255 (2016).
47. Lan, Y. & Rogers, M. A. 12-Hydroxystearic acid SAFiNs in aliphatic diols – a molecular oddity. *CrystEngComm* **17**, 8031–8038 (2015).
48. Datta, S. & Bhattacharya, S. Multifarious facets of sugar-derived molecular gels: molecular features, mechanisms of self-assembly and emerging applications. *Chem. Soc. Rev.* **44**, 5596–5637 (2015).
49. Basu, N., Chakraborty, A. & Ghosh, R. Carbohydrate derived organogelators and the corresponding functional gels developed in recent time. *Gels* **4**, (2018).
50. Morris, J., Bietsch, J., Bashaw, K. & Wang, G. Recently developed carbohydrate based gelators and their applications. *Gels* **7**, 1–61 (2021).
51. Tomasini, C. & Castellucci, N. Peptides and peptidomimetics that behave as low molecular weight gelators. *Chem. Soc. Rev.* **42**, 156–172 (2013).
52. Mondal, S., Das, S. & Nandi, A. K. A Review on Recent Advances in Polymer and Peptide Hydrogels. *Soft Matter* **16**, 1404–1454 (2020).
53. Bhardwaj, V. & Ballabh, A. Design, synthesis, and application of a new series of organogelator using crystal engineering approach and solvent parameter study: A synergetic approach. *J. Mol. Liq.* **322**, 114520 (2021).
54. Buerkle, L. E. & Rowan, S. J. Supramolecular gels formed from multi-component low molecular weight species. *Chem. Soc. Rev.* **41**, 6089–6102 (2012).
55. Hirst, A. R. & Smith, D. K. Two-Component Gel-Phase Materials—Highly Tunable Self-Assembling Systems. *Chem. Eur. J.* **11**, 5496–5508 (2005).
56. Raeburn, J. & Adams, D. J. Multicomponent low molecular weight gelators. *Chem. Commun.* **51**, 5170–5180 (2015).
57. Žinić, M., Vögtle, F. & Fages, F. Cholesterol-Based Gelators. *Top. Curr. Chem.* **256**, 39–76 (2005).
58. Willemen, H. M., Vermonden, T., Marcelis, A. T. M. & Sudho, E. J. R. Alkyl Derivatives of Cholic Acid as Organogelators : One-Component and Two-Component Gels. *Langmuir* **18**, 7102–7106 (2002).
59. Agarwal, D. S., Gogoi, N., Chowdhury, D. & Sakhuja, R. Amino acid appended cholic acid-azobenzene dyad: An effective & smart phase selective gelator for aromatic solvents. *RSC Adv.* **6**, 76632–76641 (2016).
60. Panja, A., Raza, R. & Ghosh, K. Cholesterol-Coupled Diazine-Phenol Gelator: Cyanide Sensing, Phase-Selective Gelation in Oil Spill Recovery and Dye Adsorption. *ChemistrySelect* **5**, 11874–11881 (2020).
61. Svobodová, H., Noponen, V., Kolehmainen, E. & Sievänen, E. Recent advances in steroidal supramolecular gels. *RSC Adv.* **2**, 4985–5007 (2012).
62. Tam, A. Y.-Y. & Yam, V. W.-W. Recent advances in metallogels. *Chem Soc Rev* **42**, 1540–1567 (2013).
63. Puranik, A. A., Salunke, P. S. & Kulkarni, N. D. Supramolecular birefringent metallogels formed by Trinuclear Copper(II) complexes with myo-inositol and bipyridyl ligands. *New J. Chem.* **43**, 14720–17727 (2019).
64. Kuosmanen, R., Rissanen, K. & Sievänen, E. Steroidal supramolecular metallogels. *Chem. Soc. Rev.* **49**, 1977–1998 (2020).
65. Djabourov, M. Gels. in *NMR and MRI of Gels* (ed. Deene, Y. De) 1–44 (Royal Society of Chemistry, 2020).
66. Draper, E. R. & Adams, D. J. How should multicomponent supramolecular gels be characterised ? *Chem. Soc. Rev.* **47**, 3395–3405 (2018).
67. Yu, G., Yan, X., Han, C. & Huang, F. Characterization of supramolecular gels. *Chem.*

Soc. Rev. **42**, 6697–6722 (2013).
68. Nebot, V. J. & Smith, D. K. Chapter 2. Techniques for the Characterisation of Molecular Gels. in *Functional Molecular Gels* (eds. Escuder, B. & Miravet, J. F.) 30–66 (The Royal Society of Chemistry, 2014).
69. Denzer, B. R., Kulchar, R. J., Huang, R. B. & Patterson, J. Advanced methods for the characterization of supramolecular hydrogels. *Gels* **7**, 1–29 (2021).
70. Brinksma, J., Feringa, B. L., Kellogg, R. M., Vreeker, R. & Van Esch, J. Rheology and thermotropic properties of bis-urea-based organogels in various primary alcohols. *Langmuir* **16**, 9249–9255 (2000).
71. Hassan, P. A., Raghavan, S. R. & Kaler, E. W. Microstructural changes in SDS micelles induced by hydrotropic salt. *Langmuir* **18**, 2543–2548 (2002).
72. Liu, Y., Yu, Y., Gao, J., Wang, Z. & Zhang, X. Water-Soluble Supramolecular Polymerization Driven by Multiple Host-Stabilized Charge-Transfer Interactions. *Angew. Chem. Int. Ed.* **49**, 6576–6579 (2010).
73. Srinivasan, S., Babu, S. S., Praveen, V. K. & Ajayaghosh, A. Carbon Nanotube Triggered Self-Assembly of Oligo(p-phenylene vinylene)s to Stable Hybrid π-Gels. *Angew. Chem. Int. Ed.* **47**, 5746–5749 (2008).
74. Zhang, J., Xu, X.-D., Chen, L.-J., Luo, Q., Wu, N.-W., Wang, D.-X., Zhao, X.-L. & Yang, H.-B. Platinum Acetylide Complexes Containing Iptycene as Cores: A New Family of Unexpected Efficient Organometallic Gelators. *Organometallics* **30**, 4032–4038 (2011).
75. Panja, S., Dietrich, B., Smith, A. J., Seddon, A. & Adams, D. J. Controlling Self-Sorting versus Co-assembly in Supramolecular Gels. *ChemSystemsChem* **4**, e202200008 (2022).
76. Lan, Y., Corradini, M. G., Liu, X., May, T. E., Borondics, F., Weiss, R. G. & Rogers, M. A. Comparing and correlating solubility parameters governing the self-assembly of molecular gels using 1,3:2,4-dibenzylidene sorbitol as the gelator. *Langmuir* **30**, 14128–14142 (2014).
77. Bayliss, N. S. & McRae, E. G. Solvent effects in the spectra of acetone, crotonaldehyde, nitromethane and nitrobenzene. *J. Phys. Chem.* **58**, 1006–1011 (1954).
78. Reichardt, C. *Solvents and Solvent Effects in Chemisry*. (Weinheim, Germany, 1988).
79. Lan, Y., Corradini, M. G., Weiss, R. G., Raghavan, S. R. & Rogers, M. A. To gel or not to gel: correlating molecular gelation with solvent parameters. *Chem. Soc. Rev.* **44**, 6035–6058 (2015).
80. Barton, A. F. M. Solubility Parameters. *Chem. Rev.* **75**, 731–753 (1975).
81. Zhu, G. & Dordick, J. S. Solvent effect on organogel formation by low molecular weight molecules. *Chem. Mater.* **18**, 5988–5995 (2006).
82. Nasr, P., Corradini, M. G., Hill, J., Read, S. T., Rosendahl, S. M., Weiss, R. G., Auzanneau, F. & Rogers, M. A. Hansen Solubility Parameters Clarify the Role of the Primary and Secondary Hydroxyl Groups on the Remarkable Self-Assembly of 1:3,2:4-Dibenzylidene Sorbitol. *J. Phys. Chem. C* **124**, 26455–26466 (2020).
83. Raynal, M. & Bouteiller, L. Organogel formation rationalized by Hansen solubility parameters. *Chem. Commun.* **47**, 8271–8273 (2011).
84. Bonnet, J., Suissa, G., Raynal, M. & Bouteiller, L. Organogel formation rationalized by Hansen solubility parameters: Dos and don'ts. *Soft Matter* **10**, 3154–3160 (2014).
85. Muro-Small, M. L., Chen, J. & McNeil, A. J. Dissolution parameters reveal role of structure and solvent in molecular gelation. *Langmuir* **27**, 13248–13253 (2011).
86. Waghorne, W. E. A Study of Kamlet–Taft β and π* Scales of Solvent Basicity and Polarity/Polarizability Using Computationally Derived Molecular Properties. *J. Solution Chem.* **49**, 466–485 (2020).

87. Rosa Nunes, D., Reche-Tamayo, M., Ressouche, E., Raynal, M., Isare, B., Foury-Leylekian, P., Albouy, P. A., Brocorens, P., Lazzaroni, R. & Bouteiller, L. Organogel Formation Rationalized by Hansen Solubility Parameters: Shift of the Gelation Sphere with the Gelator Structure. *Langmuir* **35**, 7970–7977 (2019).
88. Edwards, W., Lagadec, C. A. & Smith, D. K. Solvent–gelator interactions—using empirical solvent parameters to better understand the self-assembly of gel-phase materials understand the self-assembly of gel-phase materials. *Soft Matter* **7**, 110–117 (2011).
89. Lin, P., Zhang, N. X., Li, J. J., Zhang, J., Liu, J. H., Zhang, B. & Song, J. To gel or not to gel: A prior prediction of gelation in solvent mixtures. *Chinese Chem. Lett.* **28**, 771–776 (2017).
90. Sun, Z., Li, Z., Qu, K., Zhang, Z., Niu, Y., Xu, W. & Ren, C. A review on recent advances in gel adhesion and their potential applications. *J. Mol. Liq.* **325**, 115254 (2021).
91. Williams, G. T., Haynes, C. J. E., Fares, M., Caltagirone, C., Hiscock, J. R. & Gale, P. A. Advances in applied supramolecular technologies. *Chem. Soc. Rev.* **50**, 2737–2763 (2021).
92. Banerjee, S., Das, R. K. & Maitra, U. Supramolecular gels 'in action'. *J. Mater. Chem.* **19**, 6649–6687 (2009).
93. Amabilino, D. B., Smith, D. K. & Steed, J. W. Supramolecular materials. *Chem. Soc. Rev.* **46**, 2404–2420 (2017).
94. Hirst, A. R., Escuder, B., Miravet, J. F. & Smith, D. K. High-tech applications of self-assembling supramolecular nanostructured gel-phase materials: From regenerative medicine to electronic devices. *Angew. Chemie - Int. Ed.* **47**, 8002–8018 (2008).
95. Puigmartí-Luis, J. & Amabilino, D. B. Chapter 7. Optic and Electronic Applications of Molecular Gels. in *Functional Molecular Gels* (eds. Escuder, B. & Miravet, J. F.) 195–254 (The Royal Society of Chemistry, 2014).
96. Christoff-Tempesta, T., Lew, A. J. & Ortony, J. H. Beyond covalent crosslinks: Applications of supramolecular gels. *Gels* **4**, (2018).
97. Yu, X., Chen, L., Zhang, M. & Yi, T. Low-molecular-mass gels responding to ultrasound and mechanical stress : towards. *Chem. Soc. Rev.* **43**, 5346–5371 (2014).
98. Xiong, M., Wang, C., Zhang, G. & Zhang, D. Chapter 3. Molecular Gels Responsive to Physical and Chemical Stimuli. in *Functional Molecular Gels* (eds. Escuder, B. & Miravet, J. F.) 67–94 (The Royal Society of Chemistry, 2014).
99. Jones, C. D. & Steed, J. W. Gels with sense : supramolecular materials that respond to heat, light and sound. *Chem. Soc. Rev.* **45**, 6546–6596 (2016).
100. Panja, S. & Adams, D. J. Stimuli responsive dynamic transformations in supramolecular gels. *Chem. Soc. Rev.* **50**, 5165–5200 (2021).
101. Roy, B., Saha, A., Esterrani, A. & Nandi, A. K. Time sensitive, temperature and pH responsive photoluminescence behaviour of a melamine containing bicomponent hydrogel. *Soft Matter* **6**, 3337–3345 (2010).
102. Ayabe, M., Kishida, T., Fujita, N., Sada, K. & Shinkai, S. Binary organogelators which show light and temperature responsiveness. *Org. Biomol. Chem.* **1**, 2744–2747 (2003).
103. Guo, J., Yu, X., Zhang, Z. & Li, Y. Self-healing gels triggered by ultrasound with color-tunable emission based on ion recognition. *J. Colloid Interface Sci.* **540**, 134–141 (2019).
104. Mi, W., Qu, Z., Sun, J., Sun, J., Zhang, F. & Ye, K. Luminescent non-traditional π-gels fabricated from pyrimidine derivatives bearing carbazole for the detection of acid vapors. *Dye. Pigment.* **150**, 207–215 (2018).
105. Cornwell, D. J. & Smith, D. K. Photo-patterned multi-domain multi-component hybrid hydrogels. *Chem. Commun.* **56**, 7029–7032 (2020).
106. Schlichter, L., Piras, C. C. & Smith, D. K. Spatial and temporal diffusion-control of

dynamic multi-domain self-assembled gels. *Chem. Sci.* **12**, 4162–4172 (2021).
107. Salzano de Luna, M., Marturano, V., Manganelli, M., Santillo, C., Ambrogi, V., Filippone, G. & Cerruti, P. Light-responsive and self-healing behavior of azobenzene-based supramolecular hydrogels. *J. Colloid Interface Sci.* **568**, 16–24 (2020).
108. Saito, N., Itoyama, S. & Kondo, Y. Multi-responsive organo- and hydrogelation based on the supramolecular assembly of fluorocarbon- and hydrocarbon-containing hybrid surfactants. *J. Colloid Interface Sci.* **588**, 418–426 (2021).
109. Panja, S., Dietrich, B., Shebanova, O., Smith, A. J. & Adams, D. J. Programming Gels Over a Wide pH Range Using Multicomponent Systems. *Angew. Chemie - Int. Ed.* **60**, 9973–9977 (2021).
110. Alsoliemy, A., Alrefaei, A. F., Almehmadi, S. J., Almehmadi, S. J., Hossan, A., Khalifa, M. E. & El-Metwaly, N. M. Synthesis, characterization and self-assembly of new cholesteryl-substitued sym-tetrazine: Fluorescence, gelation and mesogenic properties. *J. Mol. Liq.* **342**, (2021).
111. Miravet, J. F. & Escuder, B. Chapter 5. Molecular Gels as Containers for Molecular Recognition, Reactivity and Catalysis. in *Functional Molecular Gels* (eds. Escuder, B. & Miravet, J. F.) 117–156 (The Royal Society of Chemistry, 2014).
112. Díaz, D. D., Kühbeck, D. & Koopmans, R. J. Stimuli-responsive gels as reaction vessels and reusable catalysts. *Chem. Soc. Rev.* **40**, 427–448 (2011).
113. Wang, Q., Yang, Z., Wang, L., Ma, M. & Xu, B. Molecular hydrogel-immobilized enzymes exhibit superactivity and high stability in organic solvents. *Chem. Commun.* 1032–1034 (2007).
114. Rodríguez-Llansola, F., Miravet, J. F. & Escuder, B. Supramolecular catalysis with extended aggregates and gels: Inversion of stereoselectivity caused by self-assembly. *Chem. - A Eur. J.* **16**, 8480–8486 (2010).
115. Rodríguez-Llansola, F., Escuder, B., Hamley, I. W., Hayes, W. & Miravet, J. F. Structural and morphological studies of the dipeptide based l-Pro-l-Val organocatalytic gels and their rheological behaviour. *Soft Matter* **8**, 8865–8872 (2012).
116. Berdugo, C., Miravet, J. F. & Escuder, B. Substrate selective catalytic molecular hydrogels: The role of the hydrophobic effect. *Chem. Commun.* **49**, 10608–10610 (2013).
117. Singh, N. & Escuder, B. Competition versus Cooperation in Catalytic Hydrogelators for anti-Selective Mannich Reaction. *Chem. - A Eur. J.* **23**, 9946–9951 (2017).
118. Araújo, M. & Escuder, B. Transient Catalytic Activity of a Triazole-based Gelator Regulated by Molecular Gel Assembly/Disassembly. *ChemistrySelect* **2**, 854–862 (2017).
119. Araújo, M., Díaz-Oltra, S. & Escuder, B. Triazolyl-Based Molecular Gels as Ligands for Autocatalytic 'Click' Reactions. *Chem. - A Eur. J.* **22**, 8676–8684 (2016).
120. Rodon Fores, J., Criado-Gonzalez, M., Chaumont, A., Carvalho, A., Blanck, C., Schmutz, M., Serra, C. A., Boulmedais, F., Schaaf, P. & Jierry, L. Supported Catalytically Active Supramolecular Hydrogels for Continuous Flow Chemistry. *Angew. Chemie* **131**, 18993–18998 (2019).
121. Zacharias, S. C., Kamlar, M. & Sundén, H. Exploring Supramolecular Gels in Flow-Type Chemistry - Design and Preparation of Stationary Phases. *Ind. Eng. Chem. Res.* **60**, 10056–10063 (2021).
122. Piras, C. C., Slavik, P. & Smith, D. K. Self-Assembling Supramolecular Hybrid Hydrogel Beads. *Angew. Chemie Int. Ed.* **59**, 853 (2020).
123. Panja, S., Panja, A. & Ghosh, K. Supramolecular gels in cyanide sensing: A review. *Mater. Chem. Front.* **5**, 584–602 (2021).
124. Piepenbrock, M.-O. M., Lloyd, G. O., Clarke, N. & Steed, J. W. Metal- and Anion-Binding

Supramolecular Gels. *Chem. Rev.* **110**, 1960–2004 (2010).
125. Becker, T., Goh, C. Y., Jones, F., McIldowie, M. J., Mocerino, M. & Ogden, M. I. Proline-functionalised calix[4]arene: An anion-triggered hydrogelator. *Chem. Commun.* 3900–3902 (2008).
126. Cacace, M. G., Landau, E. M. & Ramsden, J. J. The Hofmeister series: salt and solvent effects on interfacial phenomena. *Quaterly Rev. Biophys.* **30**, 241–277 (1997).
127. Yang, H. H., Liu, P. P., Hu, J. P., Fang, H., Lin, Q., Hong, Y., Zhang, Y. M., Qu, W. J. & Wei, T. B. A fluorescent supramolecular gel and its application in the ultrasensitive detection of CN-by anion-π interactions. *Soft Matter* **16**, 9876–9881 (2020).
128. Ghosh, S., Jana, P. & Ghosh, K. A naphthalimide-linked new pyridylazo phenol derivative for selective sensing of cyanide ions (CN-) in sol-gel medium. *Anal. Methods* **13**, 695–702 (2021).
129. Kumar, S., Nandi, S. K., Suman, S. & Haldar, D. A new dipeptide as a selective gelator of Cu(II), Zn(II), and Pb(II). *CrystEngComm* **22**, 7975–7982 (2020).
130. Chen, X., Zhou, Y., Zhang, G., Wang, J., Guo, C. & Wang, Y. Bifunctional organogels based on pyridine-hydrazide for enrichment and detection of Cu^{2+}, Fe^{3+} and F^{-}. *Colloids Interface Sci. Commun.* **44**, 100489 (2021).
131. Ghosh, S., Ghosh, S., Baildya, N. & Ghosh, K. Dehydroabietylamine-decorated imino-phenols: Supramolecular gelation and gel phase selective detection of Fe^{3+}, Cu^{2+} and Hg^{2+} ions under different experimental conditions. *New J. Chem.* **46**, 8817–8826 (2022).
132. Wei, T. B., Zhao, Q., Li, Z. H., Dai, X. Y., Niu, Y. B., Yao, H., Zhang, Y. M., Qu, W. J. & Lin, Q. Supramolecular organogel with aggregation-induced emission for ultrasensitive detection and effective removal of Cu^{2+} and Hg^{2+} from aqueous solution. *Dye. Pigment.* **192**, 109436 (2021).
133. Yao, H., Zhou, Q., Kan, X. T., Niu, Y. B., Naeem, M., Wei, T. B., Lin, Q. & Zhang, Y. M. A signal amplification strategy for ultrasensitive detecting $H_2PO_4^{-}$ using metal coordinated supramolecular gel. *J. Mol. Liq.* **321**, 114500 (2021).
134. Mohar, M. & Das, T. Cascade sensing of iodide and fluoride by tryptophan derived low molecular weight gelator. *Colloids Interface Sci. Commun.* **30**, 100179 (2019).
135. Patel, A. M., Ray, D., Aswal, V. K. & Ballabh, A. Probing the mechanism of gelation and anion sensing capability of a thiazole based amide gelator: A case study. *Colloids Surfaces A Physicochem. Eng. Asp.* **607**, 125430 (2020).
136. Patel, A. M., Ray, D., Aswal, V. K. & Ballabh, A. Probing the supramolecular assembly in solid, solution and gel phase in uriede based thiazole derivatives and its potential application as iodide ion sensor. *J. Mol. Liq.* **362**, 119763 (2022).
137. Terech, P. Molecular Gels : A Reservoir for Organic Rod - Like Nano - Objects. in *Fullerenes , Nanotubes and Carbon Nanostructures* 293–307 (Taylor & Francis, Inc, 2007).
138. Sada, K., Takeuchi, M., Fujita, N., Numata, M. & Shinkai, S. Post-polymerization of preorganized assemblies for creating shape-controlled functional materials. *Chem. Soc. Rev.* **36**, 415–435 (2007).
139. Di Chenna, P. H. Gels as templates for the syntheses of shape-controlled nanostructured materials. *Gels* **4**, 4–5 (2018).
140. Friggeri, A., Bommel, K. J. C. Van & Shinkai, S. Chapter 25. Gels of low molecular-mass organic gelators as templates. in *Molecular Gels. Materials with Self-Assembled Fibrillar Networks* (eds. Weiss, R. G. & Terech, P.) 857–893 (Springer International Publishing, The Netherlands, 2006).
141. Kar, T. & Das, P. K. Chapter 8. Molecular Gels as Templates for Nanostructured

Materials. in *Functional Molecular Gels* (eds. Escuder, B. & Miravet, J. F.) 255–303 (The Royal Society of Chemistry, 2014).
142. Bellotto, O., Cringoli, M. C., Perathoner, S., Fornasiero, P. & Marchesan, S. Peptide gelators to template inorganic nanoparticle formation. *Gels* **7**, 1–14 (2021).
143. Hu, J. & Yang, Y. Single-handed helical polybissilsesquioxane nanotubes and mesoporous nanofibers prepared by an external templating approach using low-molecular-weight gelators. *Gels* **3**, (2017).
144. Yadav, P. & Ballabh, A. Odd–even effect in a thiazole based organogelator: understanding the interplay of non-covalent interactions on property and applications. *New J. Chem.* **39**, 721–730 (2015).
145. Wang, R., Cui, J., Wan, X. & Zhang, J. Controlled chiral arrangement of silver nanoparticles in supramolecular gels modulated by the cooling rate. *Chem. Commun.* **55**, 4949–4952 (2019).
146. Truong, W. T., Lewis, L. & Thordarson, P. Chapter 6. Biomedical Applications of Molecular Gels. in *Functional Molecular Gels* (eds. Escuder, B. & Miravet, J. F.) 157–194 (The Royal Society of Chemistry, 2014).
147. James, T. D., Sandanakaye, K. R. A. S. & Shinkai, S. A glucose-selective molecular fluorescence sensor. *Angew. Chemie-International Ed.* **33**, 2207–2209 (1994).
148. Crane, B. C., Barwell, N. P., Gopal, P., Gopichand, M., Higgs, T., James, T. D., Jones, C. M., Mackenzie, A., Mulavisala, K. P. & Paterson, W. The Development of a Continuous Intravascular Glucose Monitoring Sensor. *J. Diabetes Sci. Technol.* **9**, 751–761 (2015).
149. Shibayama, M., Li, X. & Sakai, T. Gels: From Soft Matter to BioMatter. *Ind. Eng. Chem. Res.* **57**, 1121–1128 (2018).
150. Zhang, K., Feng, Q., Fang, Z., Gu, L. & Bian, L. Structurally Dynamic Hydrogels for Biomedical Applications: Pursuing a Fine Balance between Macroscopic Stability and Microscopic Dynamics. *Chem. Rev.* **121**, 11149–11193 (2021).
151. Mehwish, N., Dou, X., Zhao, Y. & Feng, C. L. Supramolecular fluorescent hydrogelators as bio-imaging probes. *Mater. Horizons* **6**, 14–44 (2019).
152. Debnath, S. & Ulijin, R. V. Chapter 4. Enzyme-Responsive Molecular Gels. in *Functional Molecular Gels* (eds. Escuder, B. & Miravet, J. F.) 95–115 (The Royal Society of Chemistry, 2014).
153. Skilling, K. J., Citossi, F., Bradshaw, T. D., Ashford, M., Kellam, B. & Marlow, M. Insights into low molecular mass organic gelators: A focus on drug delivery and tissue engineering applications. *Soft Matter* **10**, 237–256 (2014).
154. Du, X., Zhou, J., Shi, J. & Xu, B. Supramolecular Hydrogelators and Hydrogels : From Soft Matter to Molecular Biomaterials. *Chem. Rev.* **115**, 13165–13307 (2015).
155. Gao, Y., Kuang, Y., Guo, Z.-F., Guo, Z., Krauss, I. J. & Xu, B. Enzyme-Instructed Molecular Self-assembly Confers Nanofibers and a Supramolecular Hydrogel of Taxol Derivative. *J. Am. Chem. Soc.* **131**, 13576–13577 (2009).
156. Nolan, M. C., Fuentes Caparrós, A. M., Dietrich, B., Barrow, M., Cross, E. R., Bleuel, M., King, S. M. & Adams, D. J. Optimising low molecular weight hydrogels for automated 3D printing. *Soft Matter* **13**, 8426–8432 (2017).
157. Petit, N., Dyer, J. M., Clerens, S., Gerrard, J. A. & Domigan, L. J. Oral delivery of self-assembling bioactive peptides to target gastrointestinal tract disease. *Food Funct.* **11**, 9468–9488 (2020).
158. Jervis, P. J., Amorim, C., Pereira, T., Martins, J. A. & Ferreira, P. M. T. Exploring the properties and potential biomedical applications of NSAID-capped peptide hydrogels. *Soft Matter* **16**, 10001–10012 (2020).

159. Parveen, R. & Dastidar, P. Supramolecular Gels by Design: Towards the Development of Topical Gels for Self-Delivery Application. *Chem. - A Eur. J.* **22**, 9257–9266 (2016).
160. Limón, D., Gil-Lianes, P., Rodríguez-Cid, L., Alvarado, H. L., Díaz-Garrido, N., Mallandrich, M., Baldomà, L., Calpena, A. C., Domingo, C., Aliaga-Alcalde, N., González-Campo, A. & Pérez-García, L. Supramolecular Hydrogels Consisting of Nanofibers Increase the Bioavailability of Curcuminoids in Inflammatory Skin Diseases. *ACS Appl. Nano Mater.* **5**, 13829–13839 (2022).
161. Falcone, N., Shao, T., Andoy, N. M. O., Rashid, R., Sullan, R. M. A., Sun, X. & Kraatz, H. B. Multi-component peptide hydrogels-a systematic study incorporating biomolecules for the exploration of diverse, tuneable biomaterials. *Biomater. Sci.* **8**, 5601–5614 (2020).
162. Piras, C. C., Kay, A. G., Genever, P. G., Fitremann, J. & Smith, D. K. Self-assembled gel tubes, filaments and 3D-printing with in situ metal nanoparticle formation and enhanced stem cell growth. *Chem. Sci.* **13**, 1972–1981 (2022).
163. Piras, C. C., Kay, A. G., Genever, P. G. & Smith, D. K. Self-assembled low-molecular-weight gelator injectable microgel beads for delivery of bioactive agents. *Chem. Sci.* **12**, 3958–3965 (2021).
164. Piras, C. C., Mahon, C. S., Genever, P. G. & Smith, D. K. Shaping and Patterning Supramolecular Materials Stem Cell-Compatible Dual-Network Hybrid Gels Loaded with Silver Nanoparticles. *ACS Biomater. Sci. Eng.* **8**, 1829–1840 (2021).
165. Patterson, A. K. & Smith, D. K. Two-component supramolecular hydrogel for controlled drug release. *Chem. Commun.* **56**, 11046–11049 (2020).
166. Yang, L., Gan, S., Guo, Q., Zhang, H., Chen, Q., Li, H., Shi, J. & Sun, H. Stimuli-controlled peptide self-assembly with secondary structure transitions and its application in drug release. *Mater. Chem. Front.* **5**, 4664–4671 (2021).
167. Latxague, L., Benizri, S., Gaubert, A., Tolchard, J., Martinez, D., Morvan, E., Grélard, A., Saad, A., Habenstein, B., Loquet, A. & Barthélémy, P. Bolaamphiphile-based supramolecular gels with drugs eliciting membrane effects. *J. Colloid Interface Sci.* **594**, 857–863 (2021).
168. Lim, J. Y. C., Goh, S. S., Liow, S. S., Xue, K. & Loh, X. J. Molecular Gel Sorbent Materials for Environmental Remediation and Wastewater Treatment. *J. Mater. Chem. A* **7**, 18759–18791 (2019).
169. Yue, X., Subraveti, S. N., John, G. & Raghavan, S. R. Phase-Selective Gelation of the Water Phase in an Oil-Water Mixture: An Approach Based on Oil-Activated Nanoparticle Assembly in Water. *Langmuir* **37**, 8107–8114 (2021).
170. Okesola, B. O. & Smith, D. K. Applying low-molecular weight supramolecular gelators in an environmental setting – self-assembled gels as smart materials for pollutant removal. *Chem. Soc. Rev.* **45**, 4226–4251 (2016).
171. Bhardwaj, V. & Ballabh, A. Remediation of Marine Oil Spills and Water Pollution using Low Molecular Weight Organo-Gelators. *Recent Adv. Petrochemical Sci.* **7**, 3 (2022).
172. Vibhute, A. M. & Sureshan, K. M. How Far Are We in Combating Marine Oil Spills by Using Phase-Selective Organogelators? *ChemSusChem* **13**, 5343–5360 (2020).
173. Ohsedo, Y. Low-molecular-weight organogelators as functional materials for oil spill remediation. *Polym. Adv. Technol.* **27**, 704–711 (2016).
174. Bi, H., An, C., Mulligan, C. N., Chen, Z., Lee, K., Wen, J., Qu, Z. & Chen, X. Application of Phase-Selective Organogelators (PSOGs) for Marine Oil Spill Remediation. *J. Mar. Sci. Eng.* **10**, 1111 (2022).
175. Darban, Z., Shahabuddin, S., Gaur, R. & Ahmad, I. Hydrogel-Based Adsorbent Material for the Effective Removal of Heavy Metals from Wastewater : A Comprehensive Review.

Gels **8**, 263 (2022).
176. Bhattacharya, S. & Krishnan-Ghosh, Y. First report of phase selective gelation of oil from oil/water mixtures. Possible implications toward containing oil spills. *Chem. Commun.* 185–186 (2001).
177. Vibhute, A. M., Muvvala, V. & Sureshan, K. M. A Sugar-Based Gelator for Marine Oil-Spill Recovery. *Angew. Chemie - Int. Ed.* **55**, 7782–7785 (2016).
178. Soundarajan, K. & Mohan Das, T. Sugar-benzohydrazide based phase selective gelators for marine oil spill recovery and removal of dye from polluted water. *Carbohydr. Res.* **481**, 60–66 (2019).
179. Zhuan, C., Li, Y., Yuan, X., Zhao, J. & Hou, X. A sorbitol-based phase-selective organogelator for crude oil spills treatment. *J. Appl. Polym. Sci.* **136**, 1–8 (2019).
180. Nandi, M., Maiti, B., Banerjee, S. & De, P. Hydrogen bonding driven self-assembly of side-chain amino acid and fatty acid appended poly(methacrylate)s: Gelation and application in oil spill recovery. *J. Polym. Sci. Part A Polym. Chem.* **57**, 511–521 (2019).
181. Zhang, Y., Luan, T., Cheng, Q., An, W., Tang, R., Xing, P. & Hao, A. Highly Efficient Recovery of Oils in Water via Serine-Based Organogelators. *Langmuir* **35**, 4133–4139 (2019).
182. Li, Z., Luo, Z., Zhou, J., Ye, Z., Ou, G. C., Huo, Y., Yuan, L. & Zeng, H. Monopeptide-Based Powder Gelators for Instant Phase-Selective Gelation of Aprotic Aromatics and for Toxic Dye Removal. *Langmuir* **36**, 9090–9098 (2020).
183. Yang, Y. S., Yang, C., Zhang, Y. P., Niu, W. Y. & Xue, J. J. Synthesis and self-assembly of coumarin-chalcone derivatives organogels. *Colloids Interface Sci. Commun.* **41**, 1–7 (2021).
184. Pang, S., Chen, H., Jiang, Z., Song, B., Xie, D., Zhai, Z., Cui, Z., Gu, Y. & Pei, X. Water-in-Oil Emulsion Gels Stabilized by a Low-Molecular Weight Organogelator Derived from Dehydroabietic Acid. *Langmuir* **38**, 6049–6056 (2022).
185. Bhattacharya, S., Patra, D. & Shunmugam, R. Triphenylphosphonium conjugated quaternary ammonium based gel: synthesis and potential application in the efficient removal of toxic acid orange 7 dye from aqueous solution. *New J. Chem.* **44**, 14989–14999 (2020).
186. Raza, R., Panja, A. & Ghosh, K. Diaminomalenonitrile-functionalized gelators in F-/CN-sensing, phase-selective gelation, oil spill recovery and dye removal from water. *New J. Chem.* **44**, 10275–10285 (2020).
187. Liu, D., Dai, S., Wang, L., Liu, Y. & Lu, H. A tertiary amine group-based organogelator with pH-trigger recyclable property. *New J. Chem.* **45**, 7210–7216 (2021).
188. Fan, K., Wang, X., Wang, X., Yang, H., Han, G., Zhou, L. & Fang, S. One-step-synthesized D-gluconic acetal-based supramolecular organogelators with effective phase-selective gelation. *RSC Adv.* **10**, 37080–37085 (2020).
189. Bhardwaj, V. & Ballabh, A. A series of multifunctional pivalamide based Low Molecular Mass Gelators (LMOGs) with potential applications in oil-spill remediation and toxic dye removal. *Colloids Surfaces A Physicochem. Eng. Asp.* **632**, 127813 (2022).
190. Li, L., Chen, J., Wang, Z., Xie, L., Feng, C., He, G., Hu, H., Sun, R. & Zhu, H. A supramolecular gel made from an azobenzene-based phenylalanine derivative: synthesis, self-assembly, and dye adsorption. *Colloids Surfaces A Physicochem. Eng. Asp.* **628**, 127289 (2021).
191. Rizzo, C., Andrews, J. L., Steed, J. W. & D'Anna, F. Carbohydrate-supramolecular gels: Adsorbents for chromium(VI) removal from wastewater. *J. Colloid Interface Sci.* **548**, 184–196 (2019).