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Supramolecular topological hydrogels: from material design to applications

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Supramolecular topological hydrogels are a type of polymeric materials that combine the dynamic reversibility of non-covalent bonds with the structural features of covalent topological polymers, thus possessing a wide range of typical applications. This tutorial review is intended to provide an in-depth and all-around overview of the recent advancement in the field of supramolecular topological hydrogels from three perspectives: the strategy of introducing topological structures, stimulus-responsive properties, and functional applications. We firstly summarize supramolecular topological polymers and their classification and methodologies before focusing on supramolecular topological hydrogels. Subsequently, we introduced a series of common types of supramolecular topological hydrogels that respond to external stimuli (such as temperature, light, electronic) and elaborated their vital applications in self-healing materials, soft drives, adhesion, and so on. Finally, the existing challenges and future perspectives in supramolecular topological hydrogels are also highlighted to attract more research attention and promote the development of supramolecular topological hydrogels with fascinating design and versatile applications.

1. Introduction

Topological structures widely exist in both macroscopic and microscopic worlds. Various natural biological macromolecules, including DNA, RNA, and proteins, have topological structures which significantly affect their stability and physiological functions.[1,2] To explore topological behavior at the molecular level, Frisch and Wasserman first proposed the concept of chemical topology in 1961.[3] Over the past few decades, chemical topology has developed into a wide-ranging field, covering a variety of unique topics. Chemical topology, in particular, has greatly promoted the development of supramolecular chemistry and materials science. Many inventive strategies for designing and synthesizing macromolecules with highly fascinating topologies have been developed and established in this field.[4]

Hydrogels are a class of intrinsic hydrated networks polymeric materials prepared through three-dimensional crosslinking of hydrophilic polymers,[5] and are usually able to imbibe water or physiological fluids several times of their dry weight.[6,7] In general, there are two crosslinking modes for the fabrication of hydrogel materials including covalent or non-covalent crosslinks. As a result of their relatively low interaction energies and reversibility of physical interactions, hydrogels that are prepared from non-covalent physical crosslinks usually possess more dynamic properties. In addition, there can be programmed non-covalent interactions as well. Supramolecular topological hydrogels usually refer to a polymeric system formed by the self-assembly of monomers which is driven by reversible non-covalent interactions.[8] Compared with traditional covalent-bond-based polymers, the existence of non-covalent bonds in supramolecular polymer systems brings a myriad of fascinating properties such as structural dynamic adjustment, stimulus-responsiveness, self-repairing, *etc.*

In recent years, supramolecular polymers based on different topologies have attracted more and more attention from researchers and become a relatively independent but highly intersecting emerging discipline with other fields. Significantly, numerous supramolecular topologies have been designed and synthesized in the past few decades.[9] The diversity of topologies is expected to greatly expand the field of innovation in constructing novel supramolecular hydrogels.

A major focus of this review is on the materials design strategies and applications of supramolecular topological hydrogels. The common classification and topology design of supramolecular topological hydrogels are firstly presented, mainly including macrocycle-based host–guest hydrogels and mechanically interlocked hydrogels (as summarized in Fig. 1). Subsequently, a brief overview is given on supramolecular topological hydrogels with respect to their stimuli-responsive-

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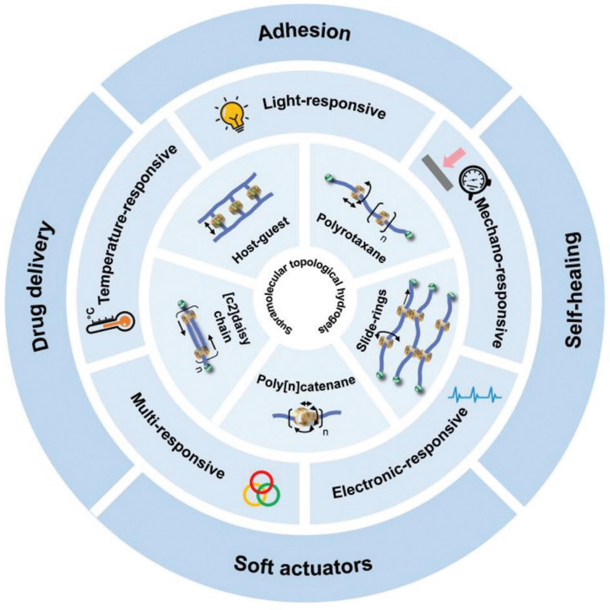

Fig. 1 Schematic illustration of main topological design, stimuli-responsive properties, and functional applications of supramolecular topological hydrogels.

ness. Then, we discuss the applications of these materials in corresponding fields, such as drug delivery, self-healing materials, adhesion materials, soft actuators, *etc.* At the end of this review, the challenges and prospects within the field of supramolecular topological hydrogels are also discussed.

2. Design and construction of supramolecular topological hydrogels

Supramolecular topological hydrogels are covalent polymers cross-linked by non-covalent interactions, such as hydrogen bonding,[10–12] host–guest recognition,[13–15] metal coordination,[16,17] π–π donor–acceptor effects,[18,19] cation–π interactions,[20] *etc.* Interestingly, these self-recognition effects of non-covalent interactions usually provide supramolecular polymeric networks with excellent stimuli-responsiveness, self-healing, shape memory, processability and recyclability.[21]

Encouraged by the power and versatility of non-covalent interactions, various strategies have been well established to fabricate supramolecular topological hydrogels. Although the synthesis methods of supramolecular hydrogels with different topological structures are quite different, they can be briefly divided into direct methods and indirect methods. The following mainly introduces the construction of supramolecular topological hydrogels based on several common supramolecular topologies.

2.1 Macrocycle-based host–guest hydrogels

The origins of supramolecular chemistry can be traced back to host–guest systems. Many supramolecular systems are self-assembled from different molecules based on structural matching and driven by numerous non-covalent interactions which are known as the host–guest systems. The guest molecules can be any organic substance with structural matching with the host molecules. Supramolecular polymers based on host–guest have fascinated scientists for the past few decades owing to their unique properties and functions.

Macrocycles generally bond to guest molecules in a manner of high selectivity and tunability. The macrocycle-based host–guest complexes are usually sensitive to external stimuli like temperature, pressure, light, or competitive guests, so that the formation and dissociation of them can be effectively controlled. By virtue of these merits, these complexes were successfully utilized to construct sophisticated supramolecular architectures and molecular machines. To date, five main type macrocycles are explored, namely crown ethers (CEs),[22] cyclodextrins (CDs),[23] calix[*n*]arenes (CA[*n*]s),[24,25] cucurbit[*n*]urils (CB[*n*]s),[26–28] and pillar[*n*]arenes (PA[*n*]s).[29,30] In recent years, other macrocycle molecules, such as a tetracationic imidazolium macrocycle, cyclobis(paraquat-*p*-phenylene) (CBPQT4^+), and calix[4]pyrroles (C4Ps), are also have been applied to prepare the supramolecular polymers.[31–33] Among them, CDs as a class of cyclic oligosaccharides obtained from starch decomposition, which have been extensively researched as host molecules. According to the number of glucose molecules contained (six, seven and eight), it generally can be divided into α-cyclodextrin (α-CD), β-cyclodextrin (β-CD), and γ-cyclodextrin (γ-CD), respectively.[34] The most distinguishing feature of CDs is that they are amphiphilic: hydrophobic on the inside and hydrophilic on the outside. Therefore, small hydrophobic molecules are often encapsulated into the cavity of cyclodextrin to form inclusion complexes.[35]

The first research on macrocycle-containing supramolecular gels appears to have been conducted in the early 1990s,[36] However, macrocycles and their host–guest chemistry have been continuously exploited for the construction of supramolecular topological hydrogels.

The macrocycles are either mediating the formation of gels as the main skeleton of the supramolecular network driven by noncovalent interactions or appended to low-molecular-weight gelators as functional groups that are not directly involved in these interactions.

2.2 Mechanically interlocked hydrogels

Supramolecules with topological features have attracted great interest in experimental[37,38] and theoretical research.[39] In the field of supramolecular topological hydrogels, the development of mechanically interlocked structures with mechanical bonds has led to new types of topologies.

The most common mechanically interlocked hydrogels are based on the main-chain polyrotaxane architecture, in which many cyclic molecules are threaded together on one polymer chain, and then trapped by capping the chain with bulky end groups. Interestingly, cyclic molecules on the polymer chains can also undergo a similar sliding motion.[40] In 1990, Harada and Kamachi firstly threaded polyethylene glycol (PEG) polymer chains through α-CD.[41] Subsequently, a molecular necklace containing many threaded α-CD was also reported by them.[42]

The successful construction of polyrotaxane hydrogels using CD laid the foundation for the research of another important class of mechanically interlocked hydrogels, named "slide-ring hydrogels". This new kind of slide-ring hydrogels was constructed through crosslinking of rotaxane moieties, was first synthesized by Kohzo Ito and Yasushi Okumura in 2001.[43] In this supramolecular topological hydrogel, PEG as a guest was pierced into the α-CD, and further capped with a large steric hindrance group, which allowed the cyclodextrin unit to move freely like a pulley. Then, the cyclodextrins are cross-linked in the shape of an "8" to generate sliding ring hydrogels.

The 'daisy-chain' structure, which contains interlocking monomeric units made of two of the main polyrotaxane constituents (the ring and the thread), is the other main type of polyrotaxanes to be explored. The most basic form of this mechanically interlocked structure is the dimer cyclic [c2] daisy chain, which can slide past each other and thus exhibit contraction or expansion. Incorporating these bonds into polymers provides a route to prepare actuating or switchable materials, as these materials based on dimer cyclic [c2]daisy chains can undergo macroscopic changes that begin with molecular motion.[44] Therefore, this fascinating molecular structure has been introduced into supramolecular topological hydrogel systems as well.

Another interesting type of mechanically interlocked ring is named catenanes. Polymeric networks contain this chain-link structure in many forms: monomeric subunits (poly[2]catenane), pendant moiety, or constituting the entire polymer (polym[2]catenane, Olympic gel, or poly[*n*]catenane). Surprisingly, the components of a catenane are unexpectedly flexible with a variety of unusual degrees of freedom, allowing them to bend, twist, and rotate.[45] However, limited by the difficulty of synthesis, there are few reports of catenane structures in supramolecular hydrogel systems so far.

3. Stimuli-responsive properties of supramolecular topological hydrogels

In nature, the physiological behavior of many creatures can be finely regulated when the external environment changes. Muscles of animals can be reversibly stiffened or softened reversibly when it receives neutral signals; Chameleons are able to change their colors depending on different environmental triggers; and the leaves of Mimosa Pudica close automatically when disturbed. Inspired by the nature, the stimuli-responsive materials have attracted considerable attention over the last few decades.[46–48]

The physical and chemical properties of supramolecular topological hydrogels are determined by the combination or synergistic effects of various intermolecular interactions. Different building blocks, topological structures and non-covalent bonds present different combinations, which greatly enriches the types of supramolecular hydrogels. From the functional aspect, the dynamic and reversible tunability of non-covalent bonds endows supramolecular topological hydrogels with interesting stimuli-responsive properties, and the incorporation of specific organic moieties as building blocks can also offer their assemblies with specific functions.

It is certainly possible to develop "smarter" materials by taking advantage of the excellent properties of supramolecular topological hydrogels. These hydrogel materials may respond to stimuli by changing their formation or by changing their properties like swelling or degradation, or even by increasing/decreasing the degree of crosslinking.[49] In this section, we will exemplify the research progress of supramolecular topological hydrogels in terms of temperature, light, mechanical force, electricity, and multiple responses, respectively.

3.1 Temperature-responsive supramolecular topological hydrogels

Temperature-responsive supramolecular topological hydrogels are particularly attractive. The hydrogels exhibit sol–gel or gel–sol transitions when generating subtle temperature changes from ambient to physiological environment.[50,51]

Generally, the formation of a supramolecular complex is usually dynamic and equilibrium governed. If there is a higher binding affinity between the host and the guest, the dynamic exchange is slower. Thus, supramolecular topological hydrogels typically undergo temperature-dependent phase transitions owing to hydrophilic–hydrophobic interactions.

Poly(pseudo)rotaxane complexes can be constructed by threading CDs with PEG chains. The stability of poly(pseudo) rotaxane is maintained by the strong interaction between the hydrophobic cavity of CD and the $-CH_2OCH_2-$ unit of the PEG chains.[52] Interestingly, PEG chains will detach from CDs at a higher temperature, as these assembly complexes are thermosensitive.[53] The temperature-responsive hydrogels given by grafted the PEG chains to the synthetic copolymers can tune the gel–sol transition in the range of 37–72 °C.[54]

According to the previous studies, the poly(*N*-isopropylacrylamide) (PNIPAM) has a lower critical solution temperature (LCST) in aqueous solution.[55] Therefore, PNIPAAm was also introduced into CD-based temperature-responsive supramolecular hydrogels, usually by modifying the polymer with CD and/or guest moieties. For example, a temperature-responsive supramolecular hydrogel was prepared using β-CD dimer and adamantyl (Ad) guest-modified PNIPAAm copolymer.[56] Due to the increased hydrophobicity of guest-modified copolymer, the LCST value of this hydrogel changed from 35 to 23 °C. In another study, star-shaped PNIPAM polymers with β-CD molecules were mixed with terminal 8-arm PEG polymers to form the supramolecular structures of β-CD-Ad host–guest complex.[57] With increasing temperature, the system underwent a sol–gel transition because of the reversible phase separation of PNIPAAM arms which bound to the 8-arm PEG through β-CD–guest interactions.

3.2 Light-responsive supramolecular topological hydrogels

Light is a non-invasive stimulus that can be used to manipulate materials remotely, easily, and quickly without the need for additional reagents.[58] In general, the light-responsiveness of supramolecular hydrogels can be induced either by the polymer network itself or by inorganic additives contained within it.[59] In the first case, the photoisomerization or photochemical reaction of light-responsive molecules in supramolecular hydrogels often leads to changes in the degree of non-covalent crosslinking.[60] For the second case, the additives mainly affected the overall photothermal reaction rather than the degree of crosslinking.[61] This is also achievable in conventional hydrogel systems.

As a class of photo-responsive molecules, azobenzene (Azo) and its derivatives exhibit interesting *trans–cis* isomerization under ultraviolet-light irradiation.[62] Besides, these molecules can be efficiently accommodated by the CDs cavity to form host–guest complexes.[63,64] Accordingly, these photoswitchable moieties have been widely used to design photo-responsive supramolecular hydrogels. For example, Harada *et al.* successfully used the α-cyclodextrins grafted glucan curdlan (CD-CUR) and Azo-modified poly(acrylic acid) (pAC12Azo) to form a photoswitchable supramolecular sol–gel system containing (Fig. 2A).[65] In this supramolecular hydrogel, a sufficient length of the main chain and enormous guest molecules make it is possible to generate multiple cross-links between CD-CUR and pAC12Azo. The connection or disconnection between the two polymers can be controlled by irradiating light with an appropriate wavelength, thereby reversibly changing the morphology of the supramolecular hydrogel.

CB[8] as another macrocycle also has been used to construct light-responsive supramolecular topological hydrogels. Zou *et al.* used a class of asymmetric Azo with CB[8] macrocycles to form homoternary supramolecular topology hydrogels (Fig. 2B).[66] Firstly, NIPAM and 2-(dimethylamino)ethyl acrylate (DMAEA) with different ratios were used to prepare copolymers. And then the DMAEA group within copolymers was modified with asymmetric Azo units. These polymers formed supramolecular hydrogels after the addition of CB[8]. Ultraviolet light disrupts supramolecular motifs *via* photoisomerization of Azo, prompting gel-to-sol transition in hydrogels. In addition, Azo changes to its *trans* configuration owing to thermal relaxation effect, resulting in rapid recovery of hydrogels within minutes at room temperature.

3.3 Mechano-responsive supramolecular topological hydrogels

Mechano-responsive materials can exhibit remarkable changes in their properties under external stress, and have attracted widespread attention. The changes in these materials include visible color changes, luminescence and fluorescence emission, small molecule release, and activation of catalytic centers, *etc.*[67]

Due to the reversible formation and dissociation of host–guest complexes, supramolecular hydrogels containing CD host–guest structures have unique mechanical properties, such as toughness, elasticity, stretchability, and self-healing properties.[68] These functions are realized by the reversible formation and dissociation of the host–guest complex. In fact,

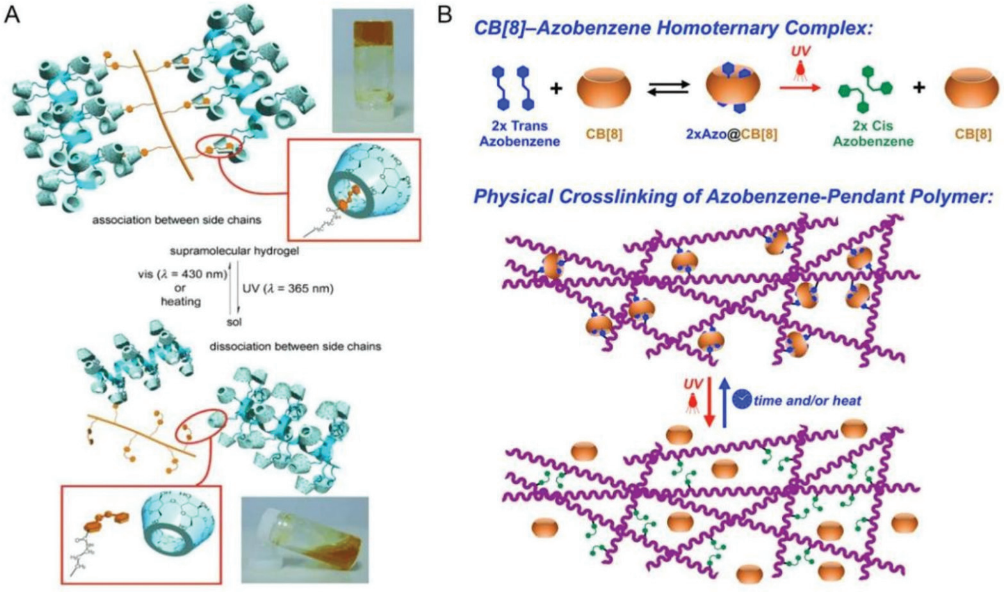

Fig. 2 Schematic illustration of light-responsive supramolecular topological hydrogels. (A) The dissociation and formation between α-CDs host and Azo moiety guest under UV and visible light (reprinted with permission from ref. 65. Copyright 2010, John Wiley and Sons). (B) The CB[8]-Azo homoternary complex disassembled and dissipated to induce a gel-to-sol transition upon photoisomerization (reprinted with permission from ref. 66. Copyright 2020, American Chemical Society).

the binding affinity of guest molecules towards CDs strongly depends on structural conformity between the guest molecules and the CD cavity based on van der Waals interactions. Because the binding strength is inversely proportional to the distance between CD host and guest molecules, slight alteration and/or restriction in the molecular structure of CD by applying an external stress may induce a reduction in inclusion ability of the β-CD moieties leading to the release of guest molecules from polymeric network.

According to this principle, Izawa *et al.* reported a novel drug controlled-release supramolecular hydrogel that could be triggered by mechanical force. This mechano-responsive supramolecular hydrogel consists of a β-CD derivative, alginate (AL), and anti-emetic drug, ondansetron (ODN). Once the mechanical compression was applied, the inclusion capacity of the CD moiety changes.[69] As a result, ODN was released from the supramolecular hydrogel (Fig. 3A). It was also shown that the release of ODN could be triggered even by the slight conformational restriction of β-CD when applied with mild external stress. This controlled-release approach provided a potential route to deliver drug on-demand through patient-generated mechanical stimuli.

Recently, Sugawara and co-workers presented a strategy to fabricate a mechano-responsive supramolecular hydrogel exhibiting stress-induced phase transition by using a combination of a thermoresponsive polymer and host–guest inclusion complex formed between β-CD and Ad (Fig. 3B).[70] This supramolecular hydrogel was prepared by utilizing a non-thermoresponsive network with β-CDs as host and a thermoresponsive PNIPAAm copolymer with Ad as guest. The dissociation of the supramolecular bonds of the host–guest complex was triggered by applying mechanical stress. This led to the exposure of the hydrophobic group, decreasing the LCST of the thermoresponsive polymer and inducing the phase transition of the polymer. This mechano-responsive phase transition strategy is helpful in the future for various application scenarios that need the control of desired functions by an applied stress, including stress detection and material patterning.

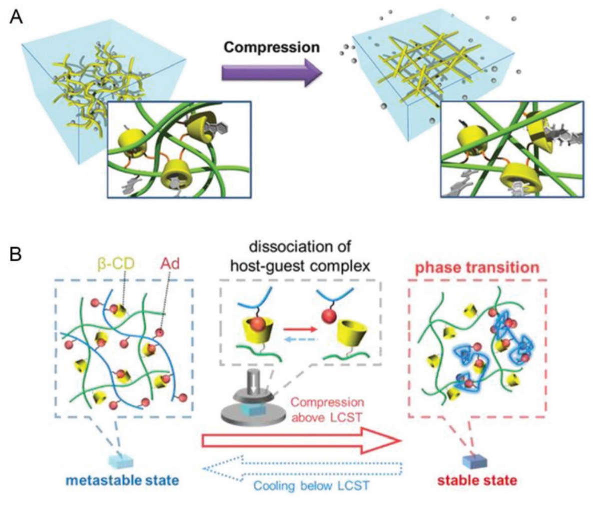

Fig. 3 Schematic illustration of mechano-responsive supramolecular hydrogels. (A) Controlled release of ODN from CD-containing supramolecular hydrogel triggered by mechanical compression (reprinted with permission from ref. 69. Copyright 2013, Royal Society of Chemistry). (B) The phase transition of supramolecular hydrogel is driven by dissociation of β-CD-Ad host–guest complex under mechanical stress (reprinted with permission from ref. 70. Copyright 2021, American Chemical Society).

3.4 Electronic-responsive supramolecular topological hydrogels

In biological systems, especially in animals, the movement of muscles is achieved by the stimulation of electrical signals sent by the brain through nerves. The electric current-sensitive artificial muscles made from hydrogels are quite interesting to explore. Similarly, supramolecular topological hydrogels with functional components can exhibit rapid response and deformation under an electric field.[71,72] However, unlike temperature and light, there are only a few supramolecular topological hydrogels response to the electric field have been reported.[73,74]

A typical example of an electric field-responsive supramolecular topology hydrogel was reported by Takashima *et al.*[75] They found that a class of cationic particle derivatives displayed electric repulsion to CD cavities (Fig. 4). The mechanical properties of these CD-based supramolecular hydrogels were influenced by the electric barrier, CD cavity size, length of the guest unit, charge number, and reductive responsiveness. In these supramolecular hydrogels, an electric barrier was introduced to the end of the alkyl guest group could increase the rupture stress. In contrast, the rupture strain is

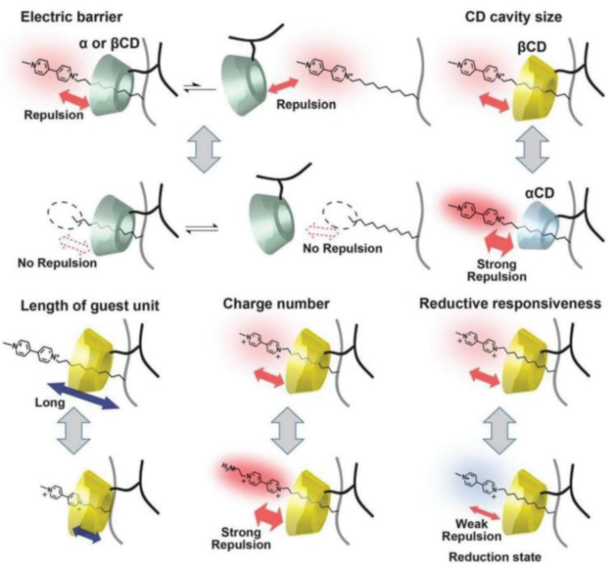

Fig. 4 The electric repulsion property of cationic guest derivatives to CD cavities is affected by an electric barrier, the CD cavity size, the length of the guest unit, the charge number, and the reductive responsiveness in electric field-responsive supramolecular topological hydrogel (reprinted with permission from ref. 75. Copyright 2018, American Chemical Society).

reduced by the electric repulsion between the CD and viologen unit. It was also found that the fracture energy was increased along with the increase of the cationic charge number on the viologen units due to the increment of dissociation energy between the CD and viologen unit.

3.5 Multi-responsive supramolecular topological hydrogels

There are various stimuli-responsive supramolecular topological hydrogel systems have been designed and reported. However, due to the inherent difficulty in preparing multi-stimulus hydrogels, most of them generally only focused on hydrogels with a single stimulus. Notably, multi-responsive supramolecular topological hydrogels can independently adjust the response to each stimulus. Therefore, it is of great significance to design and explore with multiple responses.

Liu's group successfully designed and synthesized a dual stimuli-responsive hydrogel with the four-branched molecule THPP-(PEG$_{2000}$-BA)$_4$ (Fig. 5A).[76] Under alkaline conditions THPP-(PEG$_{2000}$-BA)$_4$ decorated with benzaldehyde (BA) at the terminal end could be capped by reacting with an amine group on the CD. When the solution is adjusted to acidic, the benzoic imine bond would be hydrolyzed back to BA and ammonium. After that, α-CD passed through BA to form a PEG-α-CD inclusion complex. As a result, the solution was converted into a gel. The hydrogel was converted into a sol solution once again after a photoresponsive Azo moiety was added. This solution was transformed back into a gel when irradiated by UV light. Therefore, the reversible cycles of sol-to-gel and gel-to-sol transitions could be executed by changing the pH and UV-visible irradiation.

Itamar Willner *et al.* also developed a multi stimuli-responsive supramolecular topological hydrogel which was prepared by introducing dopamine-modified carboxymethyl cellulose (CMC) chains and self-complementary nucleic acids (Fig. 5B).[77] Due to the presence of dipyridyldithiethylene (DTE) and CMC scaffolds, a stiff hydrogel was formed and stabilized cooperatively by dopamine/DTEc (the closed state of DTE) donor–acceptor interactions and duplex nucleic acids. They used the reversible formation and dissociation of the supramolecular donor–acceptor interactions through light-induced DTE photoisomerization, or sequential oxidation and reduction of dopamine sites to switch the stiffness of supramolecular hydrogels. Another system that introduced a stimuli-responsive hydrogel triggered by one of three stimuli

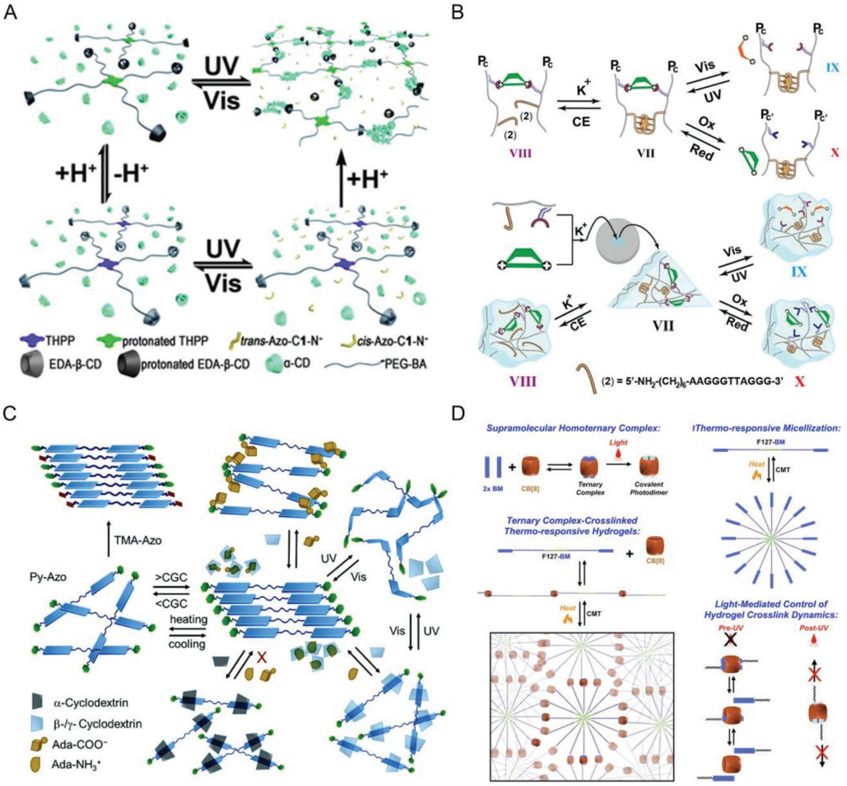

Fig. 5 Schematic illustration of multi-responsive supramolecular topological hydrogels. (A) The light/pH-responsive PPR hydrogel (reprinted with permission from ref. 76. Copyright 2013, Royal Society of Chemistry). (B) The multi stimuli-responsive supramolecular topological hydrogel showed reversible transitions between high and low stiffness states which triggered by light, redox agents and K$^+$/crown ether (reprinted with permission from ref. 77. Copyright 2018, American Chemical Society). (C) Schematic response of the main structural transformations of Py-Azo under the effects of the external environment (reprinted with permission from ref. 78. Copyright 2019, Royal Society of Chemistry). (D) The temperature-responsive hydrogel based on host–guest crosslinking of temperature-sensitive Pluronic F127 micelles through homoternary complex formation with CB[8] macrocycles (reprinted with permission from ref. 79. Copyright 2019, American Chemical Society).

was also presented. The multi-triggered stiff hydrogel with CMC chains was cross-linked synergistically by dopamine/DTEc donor–acceptor interactions and supramolecular K^+-stabilized G-quadruplexes. The G-quadruplexes could be disassembled in the presence of 18-crown-6 ether, while reformed after the addition of K^+. The hydrogel underwent reversible transitions between high and low stiffness states which triggered by light, redox agents and K^+/crown ether.

Wu and coworkers synthesized a series of bola-form surfactants with two identical Azo units distributed on both sides of the flexible chain (Fig. 5C).[78] In addition to the heating-induced reversible gel–sol transition, UV light irradiation also triggered the gel-to-sol transition, while visible light irradiation led to the opposite process. The hydrogels transformed into sols after adding the CD, then the sols would revert to gels by the addition of the other competitive guest molecules. The multiple responses of transformation between the gel and sol were achieved by the combination of light and chemical stimuli.

Recently, Zou *et al.* used *trans*-Brooker's merocyanine (BM) modified Pluronic F-127 polymers (F-127-BM) to combine with the CB[8] macrocycles at the ends of polymer chains to prepare a homoternary complex. This polymer underwent the formation of temperature-responsive micelle formation owing to host–guest interactions between CB[8] and BM guests (Fig. 5D).[79] The homoternary complex formed from polymers and particular guests could be further photo-dimerized to replace the physical host–guest interaction. This change resulted in a reduction of about two orders of magnitude in hydrogel kinetics, but temperature-responsive gelation and overall network structure remained unchanged.

Chen's group developed an effective method to prepare a novel macroscopic anisotropic bilayer hydrogel actuator with on–off switchable fluorescent color and shape change (Fig. 6).[80] A collapsed graphene oxide-PNIPAM (GO-PNIPAM) hydrogel (as a thermoresponsive layer) in conjunction with a perylene bisimide-functionalized hyperbranched polyethylenimine (PBI-HPEI) hydrogel (as a pH-responsive layer) *via* macroscopic supramolecular assembly to form a bilayer hydrogel actuator with the GO-PNIPAM hydrogel outside layer, the actuator underwent a complex shape deformation when the temperature was heated, after which the inside layer of PBI-HPEI hydrogel could be unfolded to turn on the pH-responsive fluorescence under green light.

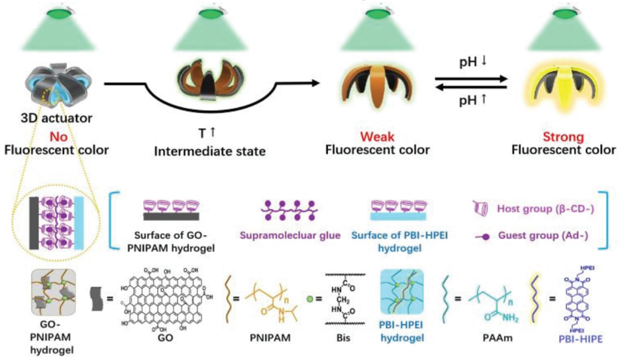

Fig. 6 Schematic illustration of the fluorescent color and 3D complex shape of the macroscopically anisotropic stimuli-responsive hydrogels changed under different stimuli (reprinted with permission from ref. 80. Copyright 2018, John Wiley and Sons).

4. Applications of supramolecular topological hydrogels

According to the requirement for specific functional applications, supramolecular topological hydrogels with multifunctional integration is necessary. Supramolecular topological hydrogels can be remolded into multi-level structures and exhibit unique multi-stimulus responsiveness. Furthermore, various functional molecule units can be introduced into the supramolecular topological networks to endow them with fascinating functional features. Therefore, supramolecular topological hydrogels have great potential for developing functional materials with specific applications. As a result, in this section, we mainly focus on the applications of supramolecular topological hydrogels in drug delivery, self-healing materials, soft actuators, and adhesive materials application progress.

4.1 Supramolecular topological hydrogels for drug delivery

Supramolecular topological hydrogels have unique biological properties, such as biodegradability, biological endogenous responsiveness, and strong binding ability with biologically active components, so they have great potential application prospects in the field of biomedicine.[81] The supramolecular topological hydrogels can provide carriers for the delivery of drugs.[82] These biofunctional molecules can be physically embedded in the hydrophobic regions of the assembly or can be designed and synthesized as carriers directly.[83] By adjusting the supramolecular interaction of the binding strength, the morphology, size and specific physicochemical properties of the material can be well controlled, resulting in direct regulation of the release kinetics.[84,85] Supramolecular hydrogels are prepared through host–guest physical cross-linking for various biomedical applications, especially used to encapsulate and release drugs. The host–guest complex could be disassembled by adding competitive guests, thereby easily adjusting the release rate.[86]

Supramolecular topological hydrogels exhibiting sol–gel transition at physiological temperature (37 °C) are highly attractive in tissue engineering as scaffolds and in biomolecules release as carriers.[87] For instance, a temperature-responsive drug-loaded supramolecular topological hydrogel can be fabricated *via* the combination of anticancer drug camptothecin (CPT) modified PEG chains and α-CD (Fig. 7A).[88] Of particular interest in this work, the gel–sol transition temperature of hydrogel is able to be tuned from 35 to 60 °C by changing the molecular weight of PEG and the ratio of α-CD. As result, the water-soluble anticancer drug 5-flfluor-

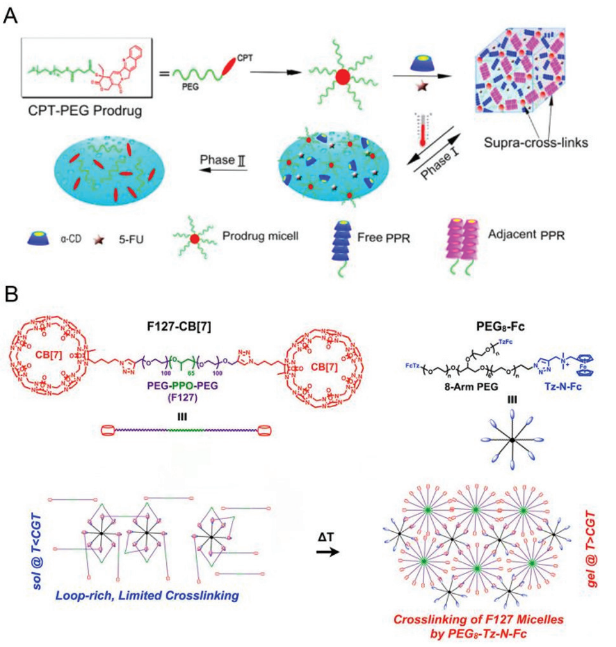

Fig. 7 Schematic illustration of supramolecular topological hydrogels for drug delivery. (A) The supramolecular poly(pseudo)rotaxane hydrogels and the temperature-responsive dual phase anticancer drug release process (reprinted with permission from ref. 88. Copyright 2014, American Chemical Society). (B) Thermoresponsive gelation entails a "loop-rich" precursor with limited cross-linking between F127-CB[7] and PEG_8-Fc, which transitions to a percolated hydrogel upon cross-linking of F127 micelles from ambient temperature to physiologic temperature for targeted drug release (reprinted with permission from ref. 89. Copyright 2019, American Chemical Society).

ouracil (5-FU) always combined with CPT in supramolecular hydrogel could enhance their anticancer activity. In another study, Zou *et al.* reported a temperature-responsive supramolecular topological hydrogel by mixed CB[7] end-modified F127 (F127-CB[7]) and ferrocene modified 8 arm PEG (PEG_8-Fc) guest to form a thermally reversible hydrogel at about 32 °C (Fig. 7B).[89] The high affinity interactions between CB[7] and Fc further ensured long-term retention of the anticancer drug Doxorubicin (DOX) at the target site, and this site can be continuously targeted with repeated dosing. These works provide design insights into novel temperature-responsive supramolecular hydrogels, and inspire future applications of supramolecular hydrogels, especially in controlled drug delivery of biomedical field.

4.2 Supramolecular topological hydrogels adhesion

In the past few decades, researchers have made great efforts to realize the adhesion between hydrogels and various soft and hard matrix materials.[71] However, the water molecules in the hydrogel can severely hinder the contact between the polymer network and the substrate surface. Even if only one layer of water molecules exists at the contact interface, the bonding force cannot be transferred to the adjacent water molecules and polymer network.[90] Therefore, in order to overcome this obstacle, the physical or chemical properties of the polymer network need to be exploited. Topological adhesion, which combines covalent bonds, interchain interactions, and polymer network entanglement as a promising strategy has emerged in recent years.[91,92] The long-chain macromolecules which have active reactive sites in the stitching polymers can be used for topological adhesion. The topological adhesion process can generally be formulated as follows: the stitching polymer precursors first diffused into the prefabricated hydrogel, then triggered mutual cross-linking *in situ*, and finally form a mechanically interlocking network. Hydrogen bonds, polyelectrolyte complexes and covalent bonds can be used to build stitched networks.[93]

Another stitch-bonding strategy that combined both chemical bonding and topological entanglement has been proposed by Lu *et al.* (Fig. 8A).[94] According to this strategy, the adhesion between arbitrary hydrogel and matrix materials was achieved. After the polymer chains diffused into the hydrogel network and crosslinked, the polymer network formed *in situ* is topologically entangled with the existing network. It was universal for hydrogels of any composition so that no specific chemical design of the hydrogel was required. Surprisingly, functional groups on polymer chains can be directly bound to the substrate surface through different chemical interactions without any surface pretreatment or chemical modification.

Similarly, Wang's group successfully designed a method of topological adhesion by using mussel-mimetic polyurethane for universal wet adhesion (Fig. 8B).[95] The key to this adhesion strategy was the use of catechol-modified stitching polymers, which can either form topological entanglements with the hydrogel network or directly bind to substrates through catechol chemistry. The results showed that the obtained mussel-like polyurethane possesses the adhesion strength of the hydrogels with universal substrates both in organics and polymers, and no need for specific functional groups or chemical modifications.

Recently, intelligent and controllable supramolecular topological hydrogel adhesion strategies have also been developed. For example, Gao and coworkers described a strategy that enables simultaneous strong adhesion and light-triggered separation.[96] They spread Fe^{3+} ions contained polymer precursors aqueous solution on the surfaces of two hydrogels. The third hydrogel network topologically entangled with the pre-existing hydrogel network was formed after crosslinking of polymer chains. Due to the coordination complexes of Fe^{3+} ions and carboxyl groups could dissociate when the Fe^{3+} ions are reduced to Fe^{2+} ions under the UV light, the photodetachable adhesion of this supramolecular topological hydrogel was achieved.

4.3 Supramolecular topological hydrogels for self-healing

Since they exhibited fast healing ability after damage under physiological conditions, hydrogels can be used as self-healing materials.[97,98] Supramolecular topological hydrogels cross-linked by non-covalent bonds have the potential to provide dynamic functions to achieve self-healing properties as the

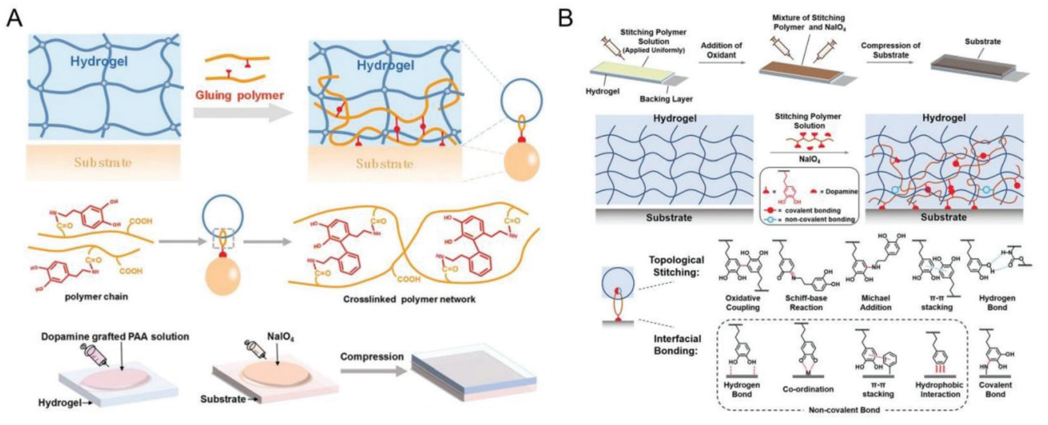

Fig. 8 Schematic illustration of supramolecular topological hydrogels for adhesion. (A) The stitch-bonding mechanism of the universal strategy for hydrogel adhesion using dopamine-grafted PAA as the glue polymer and $NaIO_4$ (reprinted with permission from ref. 94. Copyright 2020, John Wiley and Sons). (B) The experimental procedure and mechanism of the topological stitching strategy and representative interactions in topological stitching and interfacial bonding (reprinted with permission from ref. 95. Copyright 2021, John Wiley and Sons).

non-covalent bonds can be controlled efficiently and reversibly.[99,100]

A typical example of supramolecular topological hydrogels for self-healing materials based on non-covalent bonds was reported by Miyamae and co-workers.[101] According to their design, two kinds of host–guest inclusion complexes of β-CD-Ad and β-CD-Fc were introduced together to form a β-CD-Ad-Fc supramolecular topological hydrogel (Fig. 9A). The obtained β-CD-Ad-Fc supramolecular topological hydrogels showed self-healing ability when damaged and responded to redox stimuli by formation and dissociation between β-CD and Fc unit.

Recently, Nakahata *et al.* copolymerized 4-vinylphenylboronic acid (Vi-PB) and acrylamide (AAm) in an aqueous solution of hydroxypropylated polyrotaxane (HPPRx) to obtain a self-healing supramolecular topological hydrogel. The HPPRx as a slide-ring hydrogel exhibited physical self-healing due to the mobility of CD molecules in an axle polymer. Besides, the dynamic covalent bonds between boronic acid from PB residues and diol compounds from HPPRx were formed in this supramolecular topological hydrogels also made this hydrogel with excellent self-healing property (Fig. 9B).[102] This strategy of combining physical and chemical self-healing mechanisms provides a new research idea for the creation of novel self-healing materials with rapid self-healing ability in both wet and semi-dry states.

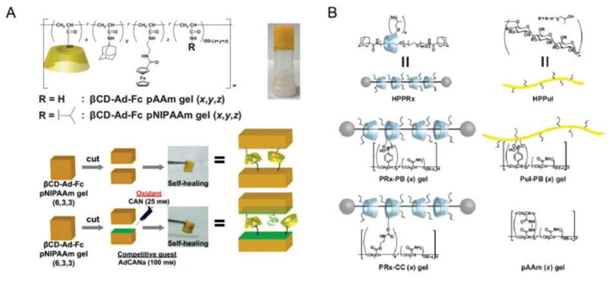

Fig. 9 Schematic illustration of supramolecular topological hydrogels for self-healing. (A) Self-healing hydrogels assembled from two kinds of non-covalent cross-links (β-CD-Ad and β-CD-Fc) show the self-healing property (reprinted with permission from ref. 101. Copyright 2015, John Wiley and Sons (https://www.wiley.com/)). (B) Self-healing hydrogels formed by cross-linked polyrotaxanes with reversible covalent bonds between boronic acid and diol (reprinted with permission from ref. 102. Copyright 2016, Elsevier).

4.4 Supramolecular topological hydrogels for soft actuators

Inspired by biological motion in nature, researchers are investigating the responsive materials with motion capabilities. For example, the motion of muscles provides useful inspiration for us to realize movement of soft actuators. Hydrogel actuators have been applied to achieve muscle-like biomimetic motion by converting input energy into visible motion.[103,104]

Noncovalent crosslinks can be formed in supramolecular hydrogel networks through host–guest interactions. Due to the tunable ability of the binding constant of host–guest inclusion complexes, the crosslinking density of the hydrogel network

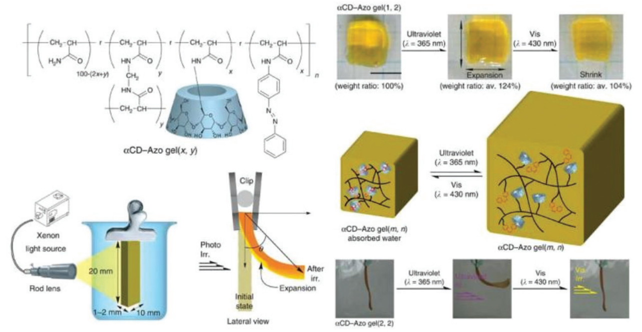

Fig. 10 Schematic illustration of photo-responsive soft actuator based on α-CD-Azo host–guest supramolecular topological hydrogel (reprinted with permission from ref. 105. Copyright 2012, Springer Nature).

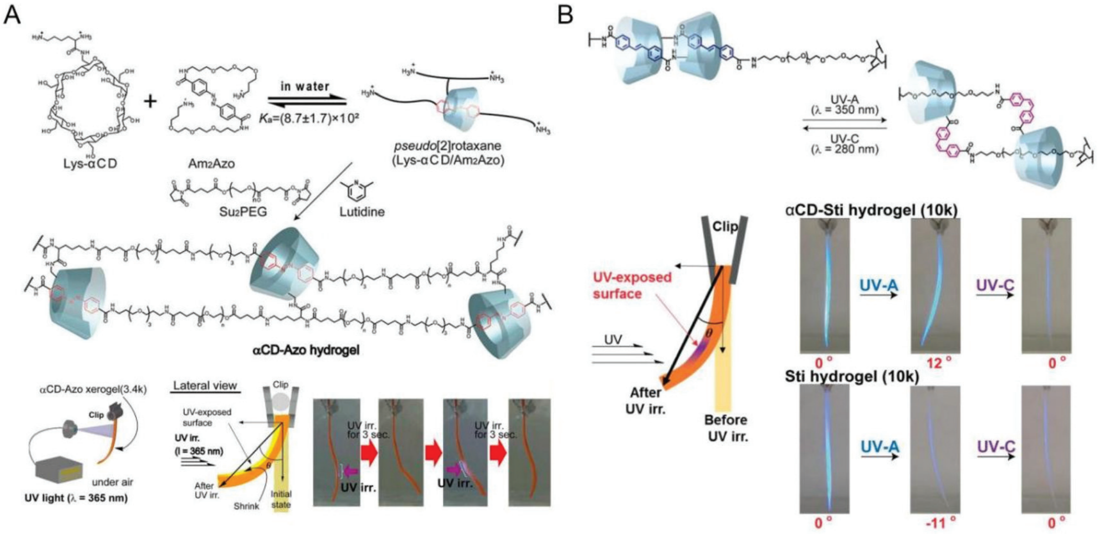

Fig. 11 Schematic illustration of photo-responsive soft actuators based on mechanically interlocked supramolecular topological hydrogels. (A) α-CD-Azo hydrogel prepared from α-CD and Azo with [2]rotaxane linker (reprinted with permission from ref. 106. Copyright 2018, American Chemical Society). (B) α-CD-Sti hydrogel prepared from α-CD and Sti with [c2]daisy chain linker (reprinted with permission from ref. 108. Copyright 2018, American Chemical Society).

can be tuned by applying external stimuli. In addition, the introduction of [2]rotaxane or [c2]daisy-chain units as topological cross-linking agents can also induce expansion-contraction of the hydrogel network by exploiting the sliding effect of the rotaxane structure. Based on the above two expansion-contraction principles, some photoresponsive supramolecular topological hydrogels have been used to fabricate soft actuators.

A novel hydrogel having both covalent and noncovalent crosslinks could be fabricated by copolymerization of AAm, *N*,*N*′-methylenebis(acrylamide), α-CD monomer, and an Azo monomer (Fig. 10).[105] Interestingly, α-CD residues were unable to encapsulate *trans*-Azo moieties, leading to swollen of the gel in the organic solvent. On the contrary, the gel underwent a shrunken in water due to the binding of α-CD moieties with *trans*-Azo moieties resulting in a higher crosslinking density of the network. When irradiated with UV light at 365 nm in aqueous media, the gel was swollen again ascribed to the dissociation of inclusion complexes as the photoisomerization of Azo moieties from the *trans* to *cis* forms. The gel went back to the shrunk state when irradiated with visible light at 430 nm owing to the reversible isomerization of Azo moieties. In addition, the gel was cut into a ribbon shape. The ribbon-shaped gel bent to the opposite direction or the same side toward the light source when irradiated with UV light or visible light. Alternant light illumination led to reversible deformations responses over at least 6 cycles.

Mechanically interlocked molecules, such as [2]rotaxane, have been introduced into the supramolecular topological hydrogel actuator. Takashima and coworkers fabricated a tough and photoresponsive α-CD-Azo hydrogel with [2]rotaxane structure unit as topological cross-links (Fig. 11A).[106] Due to the photoisomerization of the Azo moiety changing the structure of [2]rotaxane cross-links, the hydrogel actuator was reversibly deformed by irradiation with UV or visible light in water.

Besides [2]rotaxane structures, [c2]daisy chains are also have been used to build soft actuators. For instance, the Azo moiety contained [c2]daisy chain was coupled with tetra-arm PEG to generate a homogeneous hydrogel network.[107] The end-to-end distance of [c2]daisy chain became shorter due to *trans* to *cis* isomerization of Azo moieties when irradiated with UV light, resulting in the shrunk state of hydrogel. When the hydrogel was immersed in water, it bent to the direction of the 365 nm UV light source and then reversibly turned back to the initial state upon the irradiation of 430 nm visible light.

Ikejiri *et al.* prepared another photoresponsive hydrogel actuator by cross-linking of 4-arm PEG with [c2]daisy chains (Fig. 11B).[108] The obtained hydrogel actuator exhibited fast and large deformation attributed to the reversible photoisomerization of the stilbene (Sti) units in the [c2]daisy chain upon exposure to UV irradiation. It was found that photoisomerization allowed α-CD to release the *cis*-stilbene moiety and further slid onto the PEG chain, leading to the contraction of the gels. The reversible photoisomerization of the stilbene moiety was repeatable by alternating irradiation with different wavelengths of UV light.

5. Summary and outlook

Supramolecular topological hydrogels represent a novel class of versatile hydrogel materials with the advantages of fascinating structural design, controllable stimulus-responsiveness, and ease of functionalization. In the past few years, they have been extensively studied in varieties of fields and played an important role in the advancement of supramolecular chemistry and material science.

In the present review, we have described a systematic overview of the recent progress in the field of supramolecular topological hydrogels regarding the design and preparation, stimulus-responsive properties, and typically functional applications. Particularly, we highlighted the basic strategies of introducing different topological structures (host–guest complexes, mechanically interlocked moieties, *etc.*) into the hydrogel network. Benefiting from the tunability of topological structures, the corresponding hydrogel materials exhibited broad and interesting stimulus-responsiveness including temperature, light, mechanical force, electricity, and so on. Finally, we summarized recent research advances of utilizing supramolecular topological hydrogels for diverse applications, such as drug delivery, self-healing materials, soft actuators, and adhesive materials.

Despite the impressive progress that has been made in the past decade, the material design and application of supramolecular topological hydrogels is still in its infancy stage with numerous challenges. First of all, the rational design of multifunctional moieties and building blocks for their desired topological network should be further explored. Most of the reported examples are mainly focusing on the use of several common topological moieties, such as CDs and CB[*n*]s. The introduction of other supramolecular topologies will surely expand the diversity of supramolecular topological hydrogels and bring new stimulus-responsive properties and applications.

Secondly, further studies are necessary to explore the synergy of topological moieties in the hydrogel network. Theoretically, the ordered and uniform topological network should endow the hydrogel with amplified changes in response to external stimulus by synergistic effect. Nevertheless, only a few examples revealed an enormous difference in stimulus-responsiveness and functions compared with those hydrogels without a supramolecular topological network. As such, how to maximize the effectiveness of topological moieties in the hydrogel network remains a challenge. This is an important scientific concern that researchers may think about in-depth.

Although supramolecular topological hydrogels offer a wide range of applications in drug delivery, soft actuators, adhesion materials, self-healing materials, and other areas, however, the practical real-world application of supramolecular topological hydrogels is far less explored. There are only a few examples showing how to put their unique features to practical use. Therefore, more efforts are appealed to be devoted to exploring the utilization in our real life including intelligent materials and biomedical applications.

The above-mentioned challenges in the field of supramolecular topological hydrogels will be well overcome through collaborative and multidisciplinary efforts. We believe that there is a boom in employing supramolecular topological hydrogels ultimately for intelligent materials and clinical applications in the future.

Conflicts of interest

There are no conflicts to declare.

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References

1 O. Keskin, A. Gursoy, B. Ma and R. Nussinov, *Chem. Rev.*, 2008, **108**, 1225–1244.

2 J. L. Huppert, *Chem. Soc. Rev.*, 2008, **37**, 1375–1384.

3 H. L. Frisch and E. Wasserman, *J. Am. Chem. Soc.*, 1961, **83**, 3789–3795.

4 Z. Qu, S. Z. Cheng and W.-B. Zhang, *Trends Chem.*, 2021, **3**, 402–415.

5 Q. Wang, J. L. Mynar, M. Yoshida, E. Lee, M. Lee, K. Okuro, K. Kinbara and T. Aida, *Nature*, 2010, **463**, 339–343.

6 E. A. Appel, J. del Barrio, X. J. Loh and O. A. Scherman, *Chem. Soc. Rev.*, 2012, **41**, 6195–6214.

7 Y. Li, J. Rodrigues and H. Tomas, *Chem. Soc. Rev.*, 2012, **41**, 2193–2221.

8 N. M. Sangeetha and U. Maitra, *Chem. Soc. Rev.*, 2005, **34**, 821–836.

9 D. Xia, P. Wang, X. Ji, N. M. Khashab, J. L. Sessler and F. Huang, *Chem. Rev.*, 2020, **120**, 6070–6123.

10 A. Noro, Y. Matsushita and T. P. Lodge, *Macromolecules*, 2009, **42**, 5802–5810.

11 M. Guo, L. M. Pitet, H. M. Wyss, M. Vos, P. Y. Dankers and E. Meijer, *J. Am. Chem. Soc.*, 2014, **136**, 6969–6977.

12 G. Zhang, Y. Chen, Y. Deng, T. Ngai and C. Wang, *ACS Macro Lett.*, 2017, **6**, 641–646.

13 M. Lee, R. B. Moore and H. W. Gibson, *Macromolecules*, 2011, **44**, 5987–5993.

14 X. Ma and Y. Zhao, *Chem. Rev.*, 2015, **115**, 7794–7839.

15 T. Xiao, L. Xu, L. Zhou, X. Q. Sun, C. Lin and L. Wang, *J. Mater. Chem. B*, 2019, **7**, 1526–1540.

16 M. Le Bohec, M. Banère, S. Piogé, S. Pascual, L. Benyahia and L. Fontaine, *Polym. Chem.*, 2016, **7**, 6834–6842.

17 H. Liu, H. Peng, Y. Xin and J. Zhang, *Polym. Chem.*, 2019, **10**, 2263–2272.

18 L. R. Hart, J. H. Hunter, N. A. Nguyen, J. L. Harries, B. W. Greenland, M. E. Mackay, H. M. Colquhoun and W. Hayes, *Polym. Chem.*, 2014, **5**, 3680–3688.

19 H. Liu, S. Wei, H. Qiu, B. Zhan, Q. Liu, W. Lu, J. Zhang, T. Ngai and T. Chen, *Macromol. Rapid Commun.*, 2020, **41**, 2000123.

20 G. Chang, L. Yang, J. Yang, M. P. Stoykovich, X. Deng, J. Cui and D. Wang, *Adv. Mater.*, 2018, **30**, 1704234.

21 X. X. Le, Y. C. Zhang, W. Lu, L. Wang, J. Zheng, I. Ali, J. W. Zhang, Y. J. Huang, M. J. Serpe and X. T. Yang, *Macromol. Rapid Commun.*, 2018, **39**, 1800019.

22 J. S. Bradshaw and R. M. Izatt, *Acc. Chem. Res.*, 1997, **30**, 338–345.

23 G. Crini, *Chem. Rev.*, 2014, **114**, 10940–10975.

24 C. D. Gutsche, B. Dhawan, K. H. No and R. Muthukrishnan, *J. Am. Chem. Soc.*, 1981, **103**, 3782–3792.

25 S. B. Nimse and T. Kim, *Chem. Soc. Rev.*, 2013, **42**, 366–386.

26 W. Freeman, W. Mock and N. Shih, *J. Am. Chem. Soc.*, 1981, **103**, 7367–7368.

27 J. Kim, I.-S. Jung, S.-Y. Kim, E. Lee, J.-K. Kang, S. Sakamoto, K. Yamaguchi and K. Kim, *J. Am. Chem. Soc.*, 2000, **122**, 540–541.

28 S. Liu, P. Y. Zavalij and L. Isaacs, *J. Am. Chem. Soc.*, 2005, **127**, 16798–16799.

29 T. Ogoshi, S. Kanai, S. Fujinami, T.-A. Yamagishi and Y. Nakamoto, *J. Am. Chem. Soc.*, 2008, **130**, 5022–5023.

30 N. L. Strutt, H. Zhang, S. T. Schneebeli and J. F. Stoddart, *Acc. Chem. Res.*, 2014, **47**, 2631–2642.

31 L. Sambe, K. Belal, F. Stoffelbach, J. Lyskawa, F. Delattre, M. Bria, F.-X. Sauvage, M. Sliwa, V. Humblot and B. Charleux, *Polym. Chem.*, 2014, **5**, 1031–1036.

32 S. Amharar, S. Yuvayapan and A. Aydogan, *Chem. Commun.*, 2018, **54**, 829–832.

33 X. Ji, H. Wang, Y. Li, D. Xia, H. Li, G. Tang, J. L. Sessler and F. Huang, *Chem. Sci.*, 2016, **7**, 6006–6014.

34 M. E. Davis and M. E. Brewster, *Nat. Rev. Drug Discovery*, 2004, **3**, 1023–1035.

35 S. Li and W. C. Purdy, *Chem. Rev.*, 1992, **92**, 1457–1470.

36 J. Li, A. Harada and M. Kamachi, *Polym. J.*, 1994, **26**, 1019–1026.

37 H. W. Gibson and H. Marand, *Adv. Mater.*, 1993, **5**, 11–21.

38 D. B. Amabilino and J. F. Stoddart, *Chem. Rev.*, 1995, **95**, 2725–2828.

39 P.-G. de Gennes, *Phys. A*, 1999, **271**, 231–237.

40 G. Wenz and B. Keller, *Angew. Chem., Int. Ed. Engl.*, 1992, **31**, 197–199.

41 A. Harada and M. Kamachi, *Macromolecules*, 1990, **23**, 2821–2823.

42 A. Harada, J. Li and M. Kamachi, *Nature*, 1992, **356**, 325–327.

43 Y. Okumura and K. Ito, *Adv. Mater.*, 2001, **13**, 485–487.

44 J. Rotzler and M. Mayor, *Chem. Soc. Rev.*, 2013, **42**, 44–62.

45 L. F. Hart, J. E. Hertzog, P. M. Rauscher, B. W. Rawe, M. M. Tranquilli and S. J. Rowan, *Nat. Rev. Mater.*, 2021, **6**, 508–530.

46 X. Lin, X. Wang, L. Zeng, Z. L. Wu, H. Guo and D. Hourdet, *Chem. Mater.*, 2021, **33**, 7633–7656.

47 J. Zheng, P. Xiao, X. Le, W. Lu, P. Théato, C. Ma, B. Du, J. Zhang, Y. Huang and T. Chen, *J. Mater. Chem. C*, 2018, **6**, 1320–1327.

48 S. Wei, W. Lu, X. Le, C. Ma, H. Lin, B. Wu, J. Zhang, P. Theato and T. Chen, *Angew. Chem.*, 2019, **131**, 16389–16397.

49 S. Xian and M. J. Webber, *J. Mater. Chem. B*, 2020, **8**, 9197–9211.

50 A. Abdollahi, H. Roghani-Mamaqani, B. Razavi and M. Salami-Kalajahi, *Polym. Chem.*, 2019, **10**, 5686–5720.

51 Z.-X. Zhang, X. Liu, F. J. Xu, X. J. Loh, E.-T. Kang, K.-G. Neoh and J. Li, *Macromolecules*, 2008, **41**, 5967–5970.

52 M. Ceccato, P. Lo Nostro and P. Baglioni, *Langmuir*, 1997, **13**, 2436–2439.

53 X. Liao, G. Chen, X. Liu, W. Chen, F. Chen and M. Jiang, *Angew. Chem., Int. Ed.*, 2010, **122**, 4511–4515.

54 L. Ren, L. He, T. Sun, X. Dong, Y. Chen, J. Huang and C. Wang, *Macromol. Biosci.*, 2009, **9**, 902–910.

55 V. Bhalerao, S. Varghese, A. Lele and M. Badiger, *Polymer*, 1998, **39**, 2255–2260.

56 O. Kretschmann, S. W. Choi, M. Miyauchi, I. Tomatsu, A. Harada and H. Ritter, *Angew. Chem., Int. Ed.*, 2006, **45**, 4361–4365.

57 Z. X. Zhang, K. L. Liu and J. Li, *Angew. Chem., Int. Ed.*, 2013, **52**, 6180–6184.

58 M. Mauro, *J. Mater. Chem. B*, 2019, **7**, 4234–4242.

59 G. Stoychev, A. Kirillova and L. Ionov, *Adv. Opt. Mater.*, 2019, **7**, 1900067.

60 L. Li, J. M. Scheiger and P. A. Levkin, *Adv. Mater.*, 2019, **31**, 1807333.

61 D. Zhang, J. Zhang, Y. Jian, B. Wu, H. Yan, H. Lu, S. Wei, S. Wu, Q. Xue and T. Chen, *Adv. Intell. Syst.*, 2021, **3**, 2000208.

62 J. Griffiths, *Chem. Soc. Rev.*, 1972, **1**, 481–493.

63 G. Chen and M. Jiang, *Chem. Soc. Rev.*, 2011, **40**, 2254–2266.

64 Y.-L. Zhao and J. F. Stoddart, *Langmuir*, 2009, **25**, 8442–8446.

65 S. Tamesue, Y. Takashima, H. Yamaguchi, S. Shinkai and A. Harada, *Angew. Chem., Int. Ed.*, 2010, **49**, 7461–7464.

66 L. Zou, C. J. Addonizio, B. Su, M. J. Sis, A. S. Braegelman, D. Liu and M. J. Webber, *Biomacromolecules*, 2020, **22**, 171–182.

67 Y. Chen, G. Mellot, D. van Luijk, C. Creton and R. P. Sijbesma, *Chem. Soc. Rev.*, 2021, **50**, 4100–4140.

68 T. Kakuta, Y. Takashima and A. Harada, *Macromolecules*, 2013, **46**, 4575–4579.

69 H. Izawa, K. Kawakami, M. Sumita, Y. Tateyama, J. P. Hill and K. Ariga, *J. Mater. Chem. B*, 2013, **1**, 2155–2161.

70 A. Sugawara, T.-A. Asoh, Y. Takashima, A. Harada and H. Uyama, *ACS Macro Lett.*, 2021, **10**, 971–977.

71 H. L. Lim, J. C. Chuang, T. Tran, A. Aung, G. Arya and S. Varghese, *Adv. Funct. Mater.*, 2011, **21**, 55–63.

72 M. Yoshio, Y. Shoji, Y. Tochigi, Y. Nishikawa and T. Kato, *J. Am. Chem. Soc.*, 2009, **131**, 6763–6767.

73 S. K. Samanta and S. Bhattacharya, *J. Mater. Chem. A*, 2012, **22**, 25277–25287.

74 H. Wang, C. N. Zhu, H. Zeng, X. Ji, T. Xie, X. Yan, Z. L. Wu and F. Huang, *Adv. Mater.*, 2019, **31**, 1807328.

75 Y. Takashima, K. Otani, Y. Kobayashi, H. Aramoto, M. Nakahata, H. Yamaguchi and A. Harada, *Macromolecules*, 2018, **51**, 6318–6326.

76 L. Zhou, J. Li, Q. Luo, J. Zhu, H. Zou, Y. Gao, L. Wang, J. Xu, Z. Dong and J. Liu, *Soft Matter*, 2013, **9**, 4635–4641.

77 Z. Li, G. Davidson-Rozenfeld, M. Vázquez-González, M. Fadeev, J. Zhang, H. Tian and I. Willner, *J. Am. Chem. Soc.*, 2018, **140**, 17691–17701.

78 C. Yin, F. Jiang, B. Li and L. Wu, *Soft Matter*, 2019, **15**, 5034–5041.

79 L. Zou, B. Su, C. J. Addonizio, I. Pramudya and M. J. Webber, *Biomacromolecules*, 2019, **20**, 4512–4521.

80 C. Ma, W. Lu, X. Yang, J. He, X. Le, L. Wang, J. Zhang, M. J. Serpe, Y. Huang and T. Chen, *Adv. Funct. Mater.*, 2018, **28**, 1704568.

81 M. J. Webber, E. A. Appel, E. W. Meijer and R. Langer, *Nat. Mater.*, 2016, **15**, 13–26.

82 J. Zhang and P. X. Ma, *Adv. Drug Delivery Rev.*, 2013, **65**, 1215–1233.

83 J. Zhou, J. Li, X. Du and B. Xu, *Biomaterials*, 2017, **129**, 1–27.

84 M. Qi, S. Duan, B. Yu, H. Yao, W. Tian and F.-J. Xu, *Polym. Chem.*, 2016, **7**, 4334–4341.

85 W. Tian, X. Li and J. Wang, *Chem. Commun.*, 2017, **53**, 2531–2542.

86 Y. M. Zhang, Y. H. Liu and Y. Liu, *Adv. Mater.*, 2020, **32**, 1806158.

87 P. B. Malafaya, G. A. Silva and R. L. Reis, *Adv. Drug Delivery Rev.*, 2007, **59**, 207–233.

88 W. Ha, J. Yu, X.-Y. Song, J. Chen and Y.-P. Shi, *ACS Appl. Mater. Interfaces*, 2014, **6**, 10623–10630.

89 L. Zou, A. S. Braegelman and M. J. Webber, *ACS Cent. Sci.*, 2019, **5**, 1035–1043.

90 J. Yang, R. Bai, B. Chen and Z. Suo, *Adv. Funct. Mater.*, 2020, **30**, 1901693.

91 J. Yang, R. Bai and Z. Suo, *Adv. Mater.*, 2018, **30**, 1800671.

92 Z. Li, W. Lu, T. Ngai, X. Le, J. Zheng, N. Zhao, Y. Huang, X. Wen, J. Zhang and T. Chen, *Polym. Chem.*, 2016, **7**, 5343–5346.

93 J. Steck, J. Yang and Z. Suo, *ACS Macro Lett.*, 2019, **8**, 754–758.

94 Y. Gao, J. Chen, X. Han, Y. Pan, P. Wang, T. Wang and T. Lu, *Adv. Funct. Mater.*, 2020, **30**, 2003207.

95 B. Chen, K. Lei, D. Zhu, C. Yang, C. Sun, W. Xiao, Z. Zheng and X. Wang, *Adv. Mater. Interfaces*, 2021, **8**, 2100657.

96 Y. Gao, K. Wu and Z. Suo, *Adv. Mater.*, 2019, **31**, 1806948.

97 J. Zheng, P. Xiao, W. Liu, J. Zhang, Y. Huang and T. Chen, *Macromol. Rapid Commun.*, 2016, **37**, 265–270.

98 D. L. Taylor and M. in het Panhuis, *Adv. Mater.*, 2016, **28**, 9060–9093.

99 C. Xiong, L. Zhang, M. Xie and R. Sun, *Macromol. Rapid Commun.*, 2018, **39**, 1800018.

100 S. Y. Zheng, C. Liu, L. Jiang, J. Lin, J. Qian, K. Mayumi, Z. L. Wu, K. Ito and Q. Zheng, *Macromolecules*, 2019, **52**, 6748–6755.

101 K. Miyamae, M. Nakahata, Y. Takashima and A. Harada, *Angew. Chem., Int. Ed.*, 2015, **54**, 8984–8987.

102 M. Nakahata, S. Mori, Y. Takashima, H. Yamaguchi and A. Harada, *Chem*, 2016, **1**, 766–775.

103 J. Shang, X. Le, J. Zhang, T. Chen and P. Theato, *Polym. Chem.*, 2019, **10**, 1036–1055.

104 X. Le, W. Lu, J. Zhang and T. Chen, *Adv. Sci.*, 2019, **6**, 1801584.

105 Y. Takashima, S. Hatanaka, M. Otsubo, M. Nakahata, T. Kakuta, A. Hashidzume, H. Yamaguchi and A. Harada, *Nat. Commun.*, 2012, **3**, 1270.

106 Y. Takashima, Y. Hayashi, M. Osaki, F. Kaneko, H. Yamaguchi and A. Harada, *Macromolecules*, 2018, **51**, 4688–4693.

107 K. Iwaso, Y. Takashima and A. Harada, *Nat. Chem.*, 2016, **8**, 625–632.

108 S. Ikejiri, Y. Takashima, M. Osaki, H. Yamaguchi and A. Harada, *J. Am. Chem. Soc.*, 2018, **140**, 17308–17315.