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Recent advances in the synthesis of smart hydrogels

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Understanding the surrounding atmosphere and reacting accordingly with a precise action are always fascinating features of a material. Materials that pose such responsiveness are called smart materials. Currently, research studies on smart materials are being accelerated exponentially around the world; this is also true for smart hydrogels. Smart hydrogels with various chemically and structurally responsive moieties exhibit excellent characteristics of reacting under different environmental conditions such as pH, temperature, light, electric field, and magnetic field as well as biological and chemical stimuli. These smart hydrogels are drawing the attention of researchers for a wide range of applications, for instance, in designing biomedical, industrial, agricultural, electrical, healthcare, and hygienic products. This review encompasses the latest developments in the field of smart hydrogel synthesis based on their unique features and different aspects of their responsive behaviors. Additionally, this paper covers some of the recent strategies for tuning special functional properties of smart hydrogels for targeted applications.

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1. Introduction

Nature has always inspired and intrigued researchers towards the fascinating smart behavior of materials through numerous examples, such as the touch sensitivity of the leaves of *Mimosa pudica* and Venus flytraps, the photosensitivity of sunflowers and *Codariocalyx motorius*, and the color sensitivity of chameleons.¹ Due to continuous scientific developments and innovations, an insurgence of artificially smart and intelligent materials in the form of smart hydrogels has added a new



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paradigm in the field of polymer-based biomaterials. The biomimetic nature of hydrogels has envisioned widespread applications in biomedical engineering for cell culture, drug delivery, and therapeutics. Hydrogels are water-absorbing polymeric networks and are developed to mimic many of the inherent properties of soft tissue.^{2,3} For instance, the properties of hydrogels can be tuned to mimic the biochemical, mechanical, and rheological properties and stimulus responsiveness of soft tissue.^{4,5} Smart hydrogels can undergo structural and volume phase transitions in response to external stimuli, providing enormous potential for scientific observations and various advanced multidimensional technological applications.⁶ The development of smart hydrogels as functional materials has revolutionized the field of study concerning responsive materials known as stimuli-responsive hydrogels (SRHs).⁷ Generally, SRHs are absorbent to superabsorbent⁸

materials that can react to any subtle environmental changes such as pH,⁹ temperature,¹⁰ chemical species,¹¹ ionic strength,¹² electric field,¹³ and biological conditions.^{14–16} Fig. 1 shows a classification of external factors that can instigate smart hydrogels. These wonderful characteristics have the potential to trigger many applications, for example, biomedical (*i.e.*, tissue engineering, drug delivery, and drug release),¹⁷ personal healthcare and hygienic products,¹⁸ agriculture (*i.e.*, soil moisturizing, conditioning, nutrient carrier, and erosion control),¹⁹ wastewater treatment,²⁰ sensors and actuators,^{21,22} textiles,²³ construction,²⁴ electrical,²⁵ membranes,²⁶ and flocculation.²⁷ Based on their desired application trigger, hydrogels can be synthesized by physical interactions and chemical reactions. Physical hydrogels can be developed either by the interaction between oppositely charged polyelectrolytes or oppositely charged multivalent ion/surfactants



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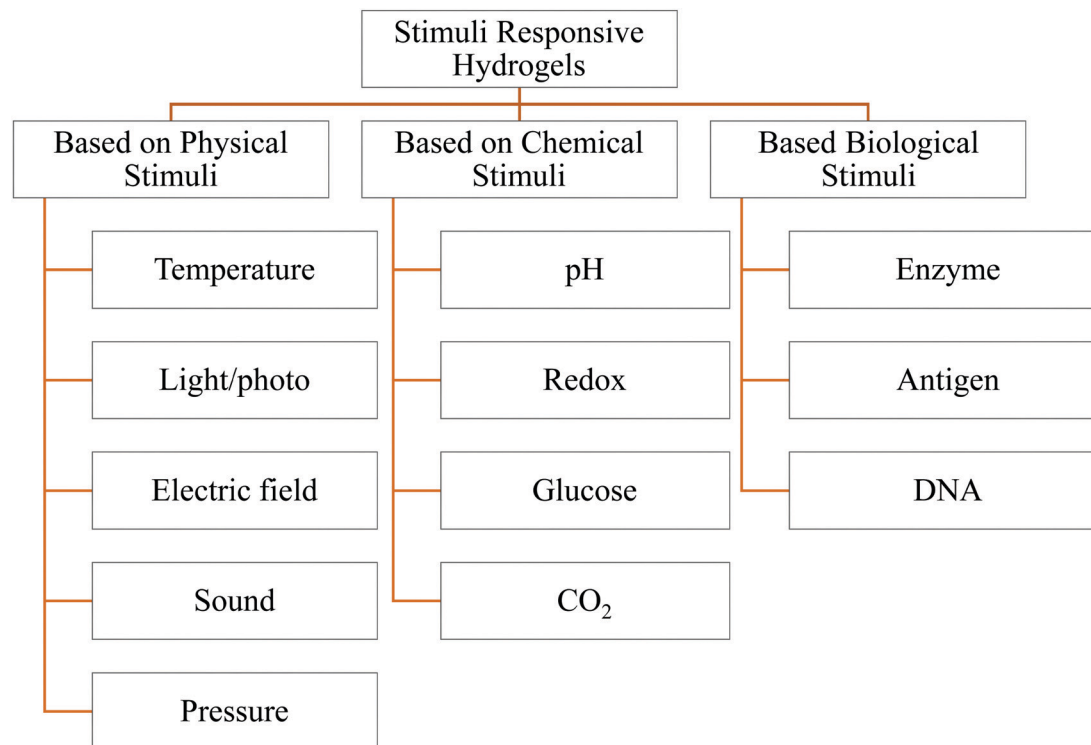


Fig. 1 Major classification of SRHs (based on ref. 48 and 58–61) [reproduced with permission from ref. 58, ©The Royal Society of Chemistry, 2014].

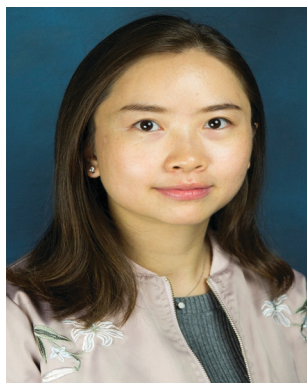
and polyelectrolytes.^{28,29} In contrast, chemical hydrogels are typically formed through a covalently crosslinked polymeric network.³⁰ These smart hydrogels are capable of swelling and shrinkage reversibly in response to changes in external environmental stimuli.⁷ These hydrogels are composed of homo-polymeric, co-polymeric, or multi-polymeric networks that are synthesized from one, two, or multiple polymers, respectively.^{29,31} Consequently, these hydrogels can display many functionalities. Such functional hydrogels can be engineered in multiple desired dimensions. For example, they can be subjected to biomedical applications by modifying their chemical structure, composition, biological functions, biodegradability, and various physicochemical properties such as mechanical and rheological, spectral, pH stability, release, and loading properties.^{32–34}

SRHs can be engineered based upon the application of external stimuli that trigger them to show a switchable sol-gel transition. External stimuli, including temperature, light, magnetic and electrical fields, and ultrasonic waves, are considered as physical triggers, while pH and redox reactions are considered as chemical triggers.³⁵ In addition, biological triggers include enzymes,^{36–40} antigens,^{14,41} and DNA.^{42–45}

During the past few decades, a plethora of research studies have been conducted to fabricate hydrogels with stimuli-responsive properties that correspond to regular hydrogel attributes such as swelling, porosity, physical structure, and modulus.^{46–48} Furthermore, the diversified properties and applications of hydrogels have resulted in thousands of research articles focusing on various aspects. In addition, numerous review articles have been found based on hydrogel applications^{49–52} and their types.^{53–57} However, a critical review addressing the techniques to tailor different functional properties and governing mechanisms of responsive behavior is yet to be amassed into a single article. This review article is therefore devoted to designing this. In this review article, we explicitly concentrated on the recent and advanced hydrogel synthesis technologies, together with process design implications, and optimized conditions of the preparation process.

2. Typical polymerization techniques for hydrogel synthesis

Hydrogels are three-dimensional polymeric networks that can absorb and contain water due to the presence of hydrophilic groups in the constituent polymeric networks. The term



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“network” implies the presence of crosslinks within hydrogels which provide pure elastic to viscoelastic properties. Hydrophilic monomers are typically used to prepare hydrogels, but hydrophobic monomers are also included to tune the physical, mechanical, and chemical properties towards specific applications. Both synthetic and natural polymeric networks can be regarded as hydrogels. Typically, synthetic polymers are hydrophobic and more chemically stronger than natural polymers. They provide a slow degradation rate and a mechanically robust structure when incorporated with natural polymers.^{62–64}

The most practical approach to producing SRHs is to combine monomers that exhibit different behaviors in response to various environmental stimuli. Any technique that is appropriate for synthesizing a cross-linked polymeric network can be applied to produce hydrogels. Free radical polymerization techniques are commonly applied to natural and/or synthetic hydrophilic monomers with multifunctional cross-linkers to produce hydrogels.³¹ The choice of the polymerization process/technique influences the properties of the resultant hydrogels greatly.⁶⁵ Hydrogels can be synthesized either through a one-step process in the form of simultaneous polymerization and crosslinking of multifunctional monomers or by a stepwise process of producing polymers with reactive groups that can crosslink themselves or can react with appropriate crosslinkers.^{31,66,67}

Composite hydrogels are developed by combining two or more types of organic, inorganic, and polymeric materials in combination to bring about the best synergistic effect of those materials for specific applications. For example, achieving desired mechanical strength and conforming to a particular shape could be achieved by incorporating hydrophobic polymer segments in the presence of crosslinkers.^{67,68}

2.1. Chain growth polymerization

Chain growth polymerization with a free radical mechanism is popular to synthesize chemically crosslinked hydrogels. The polymerization process involves three steps: initiation, propagation, and termination. Mostly hydrophilic $-C=C-$ containing monomers participate in free radical polymerization.⁶⁹ Various free radical polymerization techniques for hydrogel synthesis are described below.

Bulk polymerization (Fig. 2a) is widely applied to produce hydrogels because of its simple mechanism. This technique involves the polymerization of liquid monomers and monomer-soluble initiators with a small number of crosslinkers. The polymerization process is typically initiated using ultraviolet light, radiation, and/or chemical catalysts.⁷² Shin *et al.* synthesized pH-responsive bulk polymerized hydrogels from sodium functionalized acrylic acid (NaAAc) and hydroxyethyl methacrylate (HEMA). At first, AAc was neutralized by NaOH to get NaAAc. Afterward, the initiator (*i.e.* α,α' -azobisisobutyronitrile: AIBN) and crosslinker (*N,N'*-methylenebisacrylamide: MBAAm) along with HEMA were added to the reaction mixture. The polymerization was continued on a Petri dish for 30 minutes at 75 °C in an oven. The unreacted reaction ingredients were discarded by repeatedly washing with deionized (DI) water.⁷³ Bulk polymerization has a higher polymerization rate and inefficient heat control, and the viscosity of the reaction increases very rapidly. Therefore, it is crucial to control the conversion rate to tune the hydrogel properties. The resultant hydrogels exhibit a glassy and transparent polymer matrix, which swells and becomes flexible upon immersion into water.³¹ With the increase in reaction temperature and the initial concentration of the initiator, the rate of polymerization and conversion increases. By controlling temperature and the

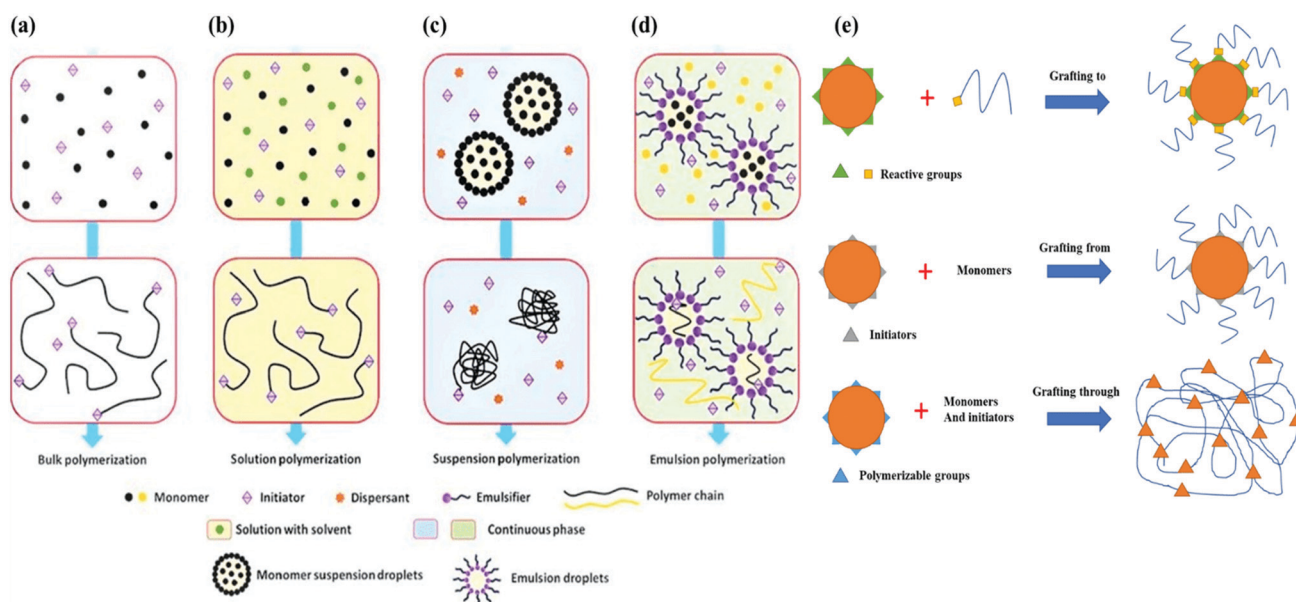


Fig. 2 Schematic diagram of the common free-radical polymerization techniques. (a) Bulk polymerization. (b) Solution polymerization. (c) Suspension polymerization. (d) Emulsion polymerization [reprinted with permission from ref. 70, ©2021 by the authors, open access under attribution 4.0 international (CC BY 4.0)]. (e) Graft polymerization techniques [reprinted with permission from ref. 71, ©2018 by the authors, open access under attribution 4.0 international (CC BY 4.0)].



concentration of the initiator, it is possible to control the conversion rate of bulk polymerization.⁷⁴ Besides, terminating the reaction at low conversion could be another approach, but in large-scale processes it is considered as uneconomical. Hence, other polymerization techniques such as solution, suspension, and emulsion polymerization are widely adopted for hydrogel synthesis.⁷⁵

2.1.1. Solution polymerization. In solution polymerization, ionic or neutral monomers with a solvent (*e.g.*, benzyl alcohol, water, ethanol, or water–ethanol mixtures) and multifunctional cross-linkers undergo polymerization by ultraviolet (UV) or redox initiation to form hydrogels. The hydrogel is separated, and the residual monomers, cross-linkers, initiators, and other impurities are extracted by washing with distilled water (Fig. 2b).⁷⁶ Solution polymerization is well-known for ease of synthesis and low-cost processing with better heat transfer control during polymerization. Since polymerization occurs in the aqueous medium, it is safe and harmless.^{72,77} Solution polymerization is greatly used for synthesizing cellulose-based superabsorbent hydrogels. The polymerization rate is high, and the reaction can be conducted at room temperature. Since the solution has low viscosity, stirring of the reaction mixture becomes easier; therefore, better heat transfer and dissipation are achieved in solution polymerization than in bulk polymerization.^{77,78} Generally, bulk and solution polymerization processes are homogenous with the potential to become heterogeneous when the formed polymer is insoluble in the monomer and solvent in the respective processes.⁷⁸

2.1.2. Suspension polymerization (including inverse-suspension polymerization). Suspension polymerization (Fig. 2c) involves generally insoluble monomers and initiators with a low hydrophilic–lipophilic balance suspending agent in aqueous solution. They are constantly agitated to create droplets of monomers (0.1–5 mm in diameter). As polymerization proceeds, the polymer hydrogel beads are formed, which can be filtered to separate from the reaction mixture.⁵⁷ Herein, individual monomers undergo small-scale bulk polymerization. Since water is the usual medium, it functions as an excellent heat transfer medium. However, a protective colloidal agent [*e.g.*, carboxymethyl cellulose (CMC) or methylcellulose (MC) and polyvinyl alcohol (PVA)] is often used to obstruct the coalescence of the droplets.⁷⁸ Inverse suspension polymerization is also widely used for hydrogel synthesis.⁷⁹

2.1.3. Emulsion polymerization (including micellar polymerization). Synthesis of hydrogels can also be done by emulsion polymerization. A typical emulsion polymerization process involves a water-soluble initiator, a surfactant, crosslinkers, and real but small water-soluble monomers (*i.e.* slightly water-soluble or completely hydrophobic monomers).^{80,81} In inverse emulsion polymerization, a hydrophilic monomer from an organic liquid is used.⁷⁶ Fig. 2d shows a typical emulsion polymerization technique. It produces polymer particles much smaller than those from suspension polymerization (0.1–3 μm). The suspension and emulsion polymerization processes can be easily controlled and heat transfer can be performed effectively over bulk polymerization.⁷⁸ In contrast to suspension polymerization, emulsion polymerization uses a water insoluble initiator.

2.1.4. Graft polymerization mechanism. Poor mechanical properties of a bulk polymerized hydrogel can be induced when

using a grafting technique, especially when grafted onto more robust support frames. Usually, free radical sites are generated on the surface of the support where monomers can be directly polymerized to form stronger covalent bonds with the support structure. For example, grafting vinyl monomers onto polysaccharides is common.³¹ Besides, grafted PAAc from hybridized chitosan (CHT) with cellulose *via* thiourea formaldehyde resin produces pH-responsive hydrogels which are mechanically more robust than grafted AAc from CHT hydrogels.⁸² Fig. 2e demonstrates a different grafting approach to synthesize hydrogels.

2.2. Step-growth polymerization

Step-growth polymerization utilizes distinct functional groups containing monomers to synthesize hydrogels. These complementary functional groups react and form covalent bonds to propagate a one-step polymerization process.⁶⁹ Tibbitt *et al.* studied the mechanical properties of photodegradable hydrogels synthesized *via* chain and step-growth polymerization processes (Fig. 3). It was demonstrated that mechanical integrity, tensile toughness, ductility, and shear strain to yield of step-growth hydrogels were better than those of chain growth hydrogels because of network homogeneity and cooperativity. However, the rate of erosion due to light exposure was less for chain-growth hydrogels due to higher network connectivity in chain-grown hydrogels.⁸³ With the understanding of hydrogel networking, desirable properties of hydrogels can be achieved.

3. Crosslinking methods of hydrogel fabrication

Since hydrogels contain hydrophilic segments, cross-linking is essential to avoid the dissolution of hydrophilic polymer segments in the aqueous medium. Without substantial cross-links, the solutions of hydrophilic polymers behave as Newtonian fluids.

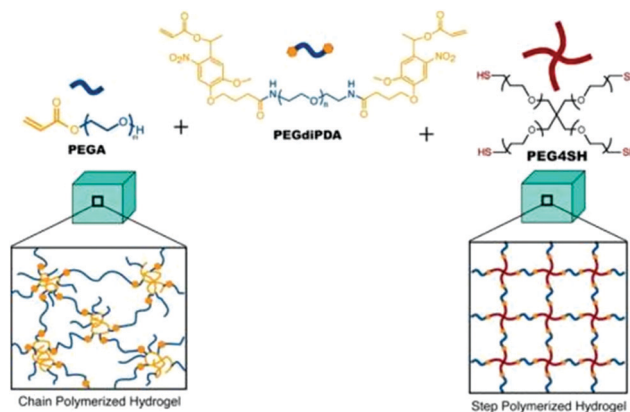


Fig. 3 Photo-degradable hydrogel based on chain and step polymerization of a photolabile monomer (PEGdiDPA). (a) Chain polymerization of PEGdiDPA and PEGA *via* free radical mechanism (*e.g.* heterogeneous network structure). (b) Step-polymerization of PEGdiDPA with PEG4SH *via* Michael-addition polymerization [reprinted with permission from ref. 83, ©American Chemical Society, 2013]. *PEGA (monoarylated poly(ethylene glycol)); poly(ethylene glycol) di-photodegradable acrylate (PEGdiDPA); four-arm poly(ethylene glycol) functionalized with thiol end groups (PEG4SH).



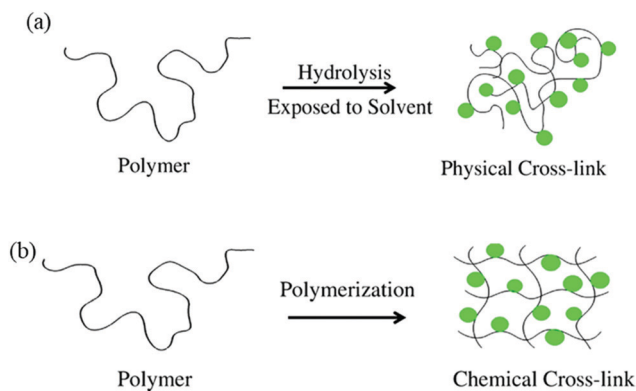


Fig. 4 Schematic illustration of hydrogel fabrication. (a) Physical cross-linking. (b) Chemical Crosslinking [reprinted with permission from ref. 77, ©Springer Nature, 2018].

On the other hand, elastic to visco-elastic behavior is achieved by increasing the number of cross-links.⁶⁶ The degree of crosslinking is correlated with overall hydrogel properties and characteristics.^{59,60}

Typically, hydrogels are classified into two categories and their 3D networks can be formed in numerous ways, as shown

in Fig. 5.⁸⁴ The first category is known as physically crosslinked hydrogels that form networks in polymers *via* physical interactions, such as ionic interactions between polycations/multivalent cations and polyanions, or hydrophobic interactions in polymer chains, and so on (Fig. 4a). The other category is called chemically crosslinked hydrogels that form networks in polymers *via* chemical interactions (*i.e.* covalent bonds). Herein, crosslinking can be instigated by heating, or ultraviolet radiation, and/or by chemical crosslinking achieved by different reactions, such as Michaelis–Arbuzov reaction, nucleophilic reaction, and Michael’s reaction, to name a few (Fig. 4b).^{85,86} Theoretically, different applications of hydrogels are possible through the optimization of their properties which is controlled by the degree of crosslinking.^{87,88}

4. Synthesis of stimulus-responsive hydrogels (SRHs)

4.1. Synthesis of thermo-responsive hydrogels (TRHs)

Hydrogels responsive to temperature are considered as one of the smartest types of hydrogels that can change their shapes and formation in response to temperature changes.⁸⁹ They are

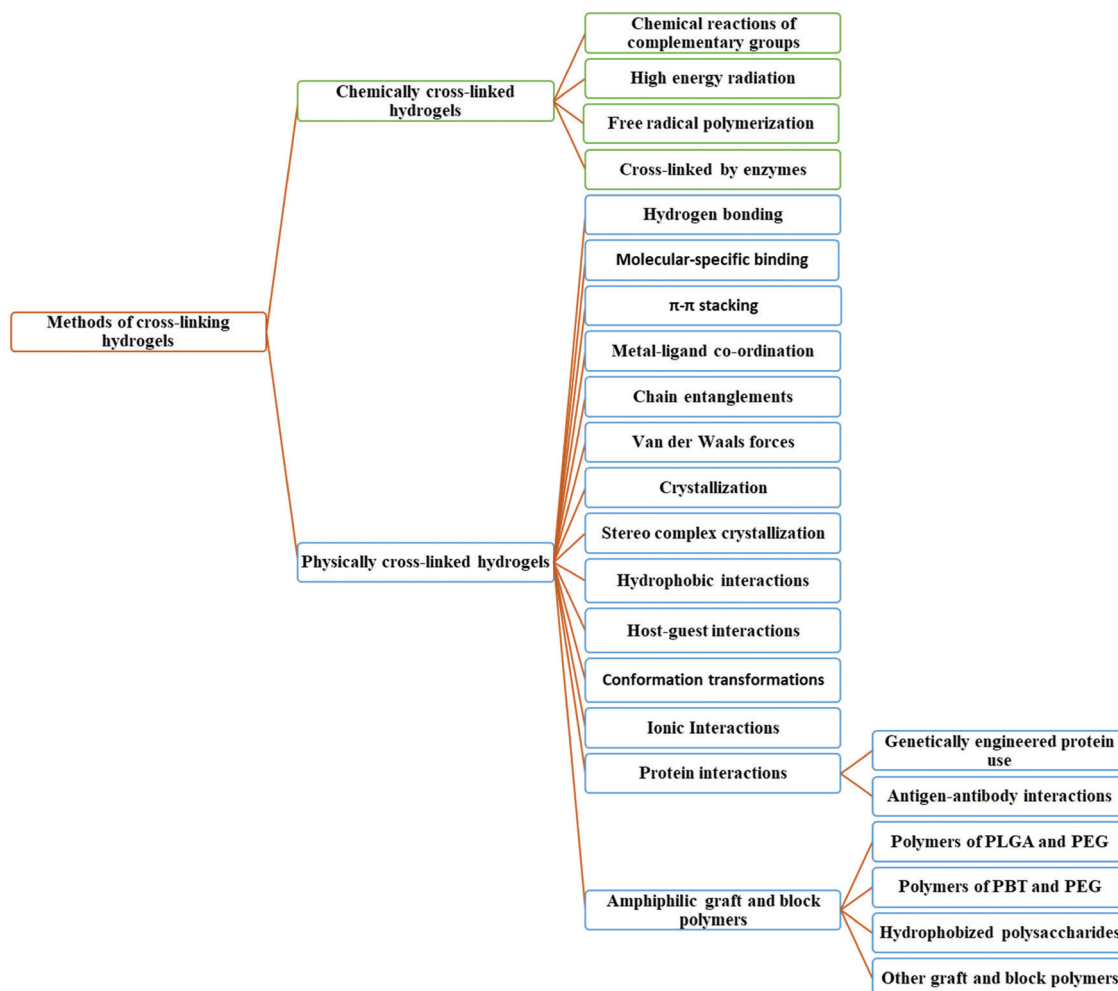


Fig. 5 Methods of cross-linking hydrogels (based on ref. 63). *Polylactic-co-glycolic acid (PLGA); polybutylene terephthalate (PBT).



Table 1 Conditions and parameters of PNIPAAm synthesis

Synthesis method	Synthesis temperature	Fluid	Crosslinkers	Reagents	Effect on PNIPAAm properties	Ref.
Free radical polymerization	22 °C	DI water	MBAAM	APS and TEMED	Increased sensitivity to temperature triggered controllable drug release and improved mechanical properties	98
Surfactant-free emulsion polymerization	70 °C	DI water	MBAAM	KPS	Improved crosslinks, charge distribution impact and temperature-responsive deswelling behavior	99
Free radical polymerization	10, 15, 20, or 25 ± 0.2 °C	DI water	MBAAM	APS and TEMED	The transition towards a turbid substrate became more gradual (at 33.5–34.5 °C) which consequently had an influence on the light scattering behavior in response to temperature	100
Free-radical precipitation copolymerization	70 °C	DI water	MBAAM	SDS, APS	The particle size can be influenced by controlling the concentration of the free radical initiator, which is a crucial factor for drug delivery	101
Sedimentation polymerization	80 °C	Silicone oil	MBAAM	KPS, TEMED	The swelling rate of the resulting hydrogel beads was directly influenced by the morphology (especially porosity in the structure) of the gel delivered by the applied polymerization	102

Abbreviations: ammonium persulfate (APS); *N,N,N',N'*-tetramethyl ethylenediamine (TEMED); potassium persulfate (KPS); sodium dodecyl sulfate (SDS); and *N,N'*-methylenebisacrylamide (MBAAM).

mainly characterized by the presence of hydrophobic groups, such as methyl, ethyl, and propyl groups.⁹⁰ Usually, TRHs can be divided into positively thermo-sensitive, negatively thermo-sensitive, and thermally reversible gels.⁹¹ Positively thermo-sensitive hydrogels swell at high temperatures and shrink at low temperatures, for instance, interpenetrating polymeric networks (IPNs) based on poly(acrylamide-*co*-butyl methacrylate) [P(NIPAAm-*co*-BMA)] and PAAc.⁹² Conversely, negatively thermo-sensitive hydrogels swell with decreasing temperature and *vice versa*. TRHs can be synthesized from both natural polymers (*e.g.*, chitosan, cellulose, and gelatin) and synthetic polymers (*e.g.* poly(*N*-isopropylacrylamide) (PNIPAAm) and polyfluorene 127).⁹³ Here, the choice of a monomer is important because the behavior of a hydrogel is largely regulated by the type of monomer and crosslinker used for the synthesis. The most common monomer, NIPAAm, is widely used to design drug release systems. Research reveals that the presence of both hydrophilic amide groups and hydrophobic isopropyl groups in side chains allows PNIPAAm to show temperature-controlled phase transition behavior in aqueous solution at a lower critical solution temperature (LCST) of around 32 °C.^{94–96} PNIPAAm is one of the most intensely studied hydrogels, especially in biomedical applications, because its volume phase transition temperature (VPTT) at LCST is close to human body temperature and due to its fast on-off switching.^{89,97} Some typical parameters and ingredients considered in the synthesis of PNIPAAm are shown in Table 1.

Another source of novel thermo-responsive hydrogels can be in the form of renewable resource-based hydrogels. It is possible to synthesize them using bacterial cellulose (BC) and castor oil, in combination with NIPAAm.¹⁰³ Most of the thermo-responsive polymers undergo phase transitions with the change of temperature.¹⁰⁴ The critical solution temperature is responsible for controlling the solubility of such hydrogels.^{47,105} The synthesis of thermo-responsive hydrogels from polymers using temperature changes as a trigger is shown in Fig. 6.

Some cellulose-based functionalized MCs with the protein laminin can be used to develop a bioactive scaffold for neural tissue engineering.¹⁰⁶ Similarly, composite thermo-sensitive hydrogels synthesized from CHT/CMC, CHT/collagen, and CHT/PEG can be alternatives to invasive surgeries.^{107–109} They can also be used

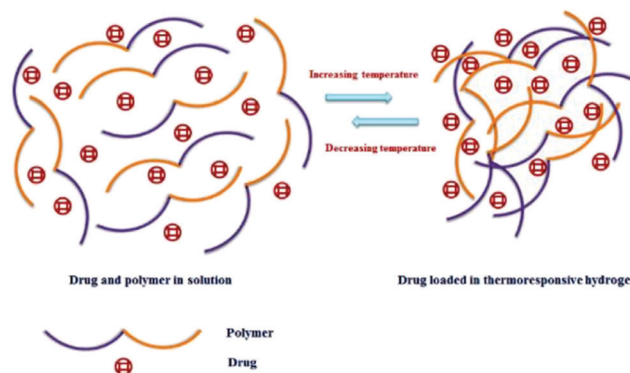


Fig. 6 Formation of TRHs using temperature as a trigger [reprinted with permission from ref. 93, ©2018 by the authors, open access under attribution 4.0 international (CC BY 4.0)].

as potential targeted drug carriers that are injected into the body as a liquid and form a gel if the body temperature rises above their LCST.⁸⁴

TRHs have become an optimum material for advanced bioprinting applications because of their easy tunability from the sol-gel state by changing temperature (rapid gelation), printability with good shape fidelity, high resolution,¹¹⁰ cell compatibility^{111,112} with the ability to mimic the micro-environment, natural shape, and vascularization.^{113,114} TRHs that are used for bioprinting can be synthesized from gelatin and its derivatives, MC, agarose, collagen, pluronic and its derivatives, PEG/polyethylene oxide (PEO) based block polymers, and poly(*N*-PNIPAAm) and its derivatives.¹¹⁵ Josegrio *et al.* developed a composite PAAm hydrogel containing silica nanoparticles (NPs) with an enhancement in the thermal diffusivity of PAAm hydrogel nanocomposites.¹¹⁶ Chu *et al.* summarized the most used techniques to fabricate and engineer different thermo-responsive smart hydrogel materials in different forms of functional compounds (shown in Fig. 7).¹¹⁷

4.2. Synthesis of light-responsive hydrogels (LRHs)

Hydrogels responsive to light show reversible deformations from a flowable state to a non-flowable state when exposed to light



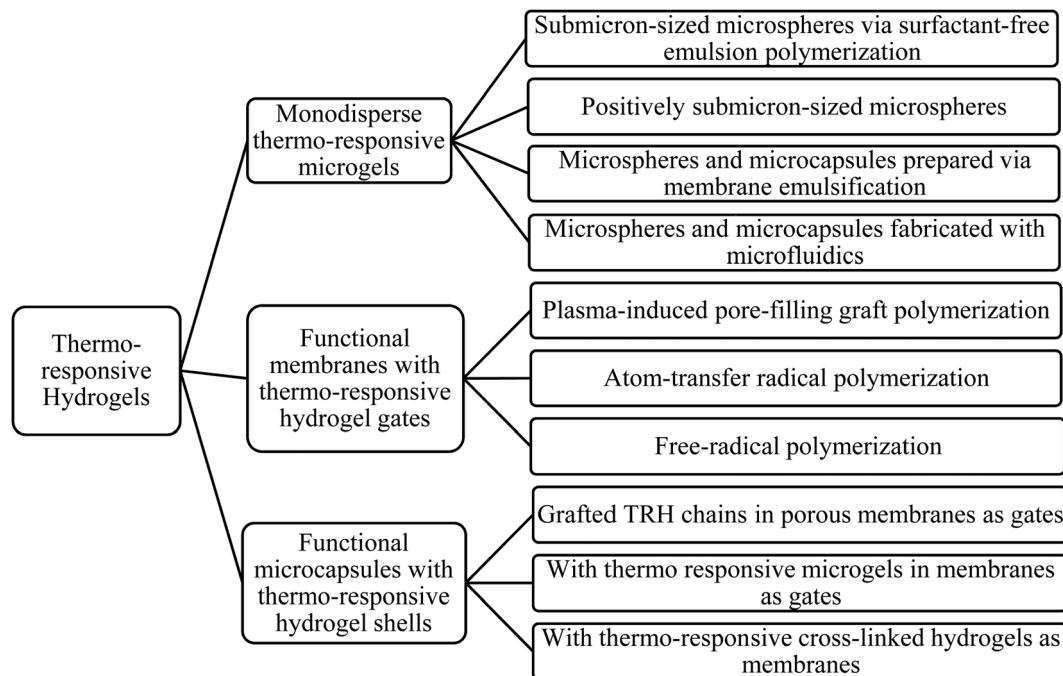


Fig. 7 Synthesis and engineering techniques for different thermo-responsive smart hydrogels (based on ref. 117).

sources such as UV light, visible light, and near IR light.^{54,118} LRHs are generally classified into two categories: one contains photolabile moieties (e.g. azobenzene and *o*-nitro benzyl) and the other contains near IR absorbing nanostructures such as nanorods, nano-shells, and carbon nanotubes embedded in thermo-responsive hydrogels.¹¹⁹ Such hydrogels are functionalized as light-sensitive through photochromism by incorporating photochromic molecules into the hydrogel matrix. This can be performed by chemical coupling or mechanical processes and controlled by the right selection of chromophores, wavelength, light intensity, and chromophore–polymer interactions.¹²⁰ These hydrogels can undergo sol–gel phase transitions due to the cleavage of photo-responsive moieties linked to the hydrogel networks, contraction–expansion of volume occurring due to photothermal heating of NPs incorporated within TRHs,¹²¹ and/or chemical modifications (as demonstrated in Fig. 8).¹²²

Ter Schiphorst *et al.* developed a light-responsive hydrogel by incorporating chromophore (photochrome) spiropyrans *via* copolymerization with NIPAAm and AAC. This hydrogel contracts and swells due to the photoisomerization of the photochrome.¹²³ In another study, the incorporation of metallic NPs such as Au, Pt, Ag, and Cu was reported to synthesize light-sensitive hydrogels due to their superior light adsorbing and/or scattering capability than molecular chromophores.¹²⁴ The light responsiveness of hydrogels based on *trans*–*cis* photoisomerization and thereby sol–gel and gel–sol transitions were reported by Zhao and Fraser Stoddart. The photoinduced *cis*–*trans* isomerization of azobenzene found applications in many hydrogel systems. The host–guest¹¹⁹ chemistry of some materials such as cyclodextrins (CDs) and their derivatives was also used in the synthesis of light-responsive hydrogels.¹²⁵ Another study suggests that the composite hydrogels of PNIPAAm synthesized with the nanofillers

of glycidyl methacrylate (GMA) functionalized graphene oxide (GO) exhibited light responsiveness due to the infrared light sensitivity of GO.¹²⁶ A light-responsive hydrogel of polymeric NPs (light-sensitive) embedded in a thermo-responsive and mechanically stable double networked hydrogel was recently developed.¹²¹ Hydrogels based on photo-responsive agents (e.g., polydopamine)¹²⁷ and semi-conductive polymers¹²⁸ were also synthesized and studied to fabricate light-responsive hydrogels.

4.3. Synthesis of electrically conductive hydrogels (ECHs)

Hydrogels responsive to electrical stimuli are typically polymeric blends or co-networks of electroactive polymers and highly hydrated hydrogels. The electroactive constituent contributes to electrical conductivity and on–off electrical and optical switching, whereas the hydrated constituent endows the swelling ability, biocompatibility, and small molecular diffusion.¹²⁹ When a water-swollen crosslinked polyelectrolyte gel (*i.e.* electroconductive hydrogels) is sandwiched between two electrodes and subject to a DC voltage, a potential gradient is generated, and based on the charges on the hydrogel it contracts anisotropically, thereby discharging the water content.^{13,48,130} Hydrogels containing ionic moieties exhibit such a contraction mechanism, whereas hydrogels with charge neutrality show zero contraction. The presence of polyanions makes hydrogels contract extensively near the anode and swell to a lesser extent near the cathode. On the contrary, hydrogels with polycations show an opposite contraction–swelling mechanism, meaning that they contract extensively near the cathode and show little swelling near the anode. Moreover, the contraction rate increases with the applied electric field.^{130–132}

The use of free radical polymerization and the chemical crosslinking approach was reported for the fabrication of



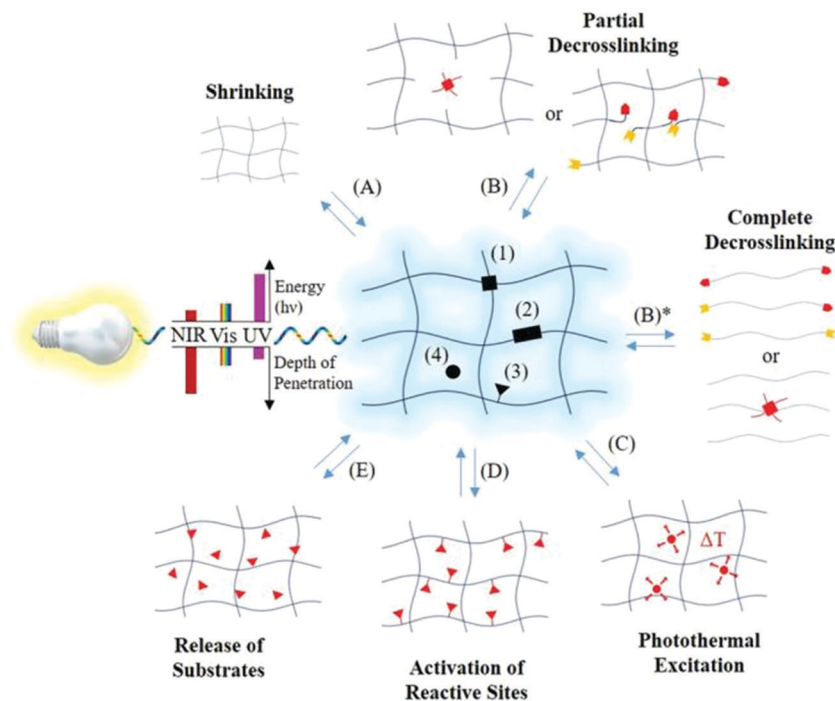


Fig. 8 Molecular architecture and responses of a photo-responsive hydrogel (center). The photo-responsive entities (black geometries) may be present at (1) crosslinking points, (2) polymer or supramolecular backbone, (3) side chains, or (4) aqueous medium of dissolved hydrogels. Based on the placement and photo-responsive moieties, photoresponses may include (A) shrinkage and (B) partial de-crosslinking (results in water uptake and thus increasing hydrogel volume). Nevertheless, increasing photoinduced crosslinking leads to hydrogel shrinkage and full de-crosslinking leads to degradation to liquefaction of hydrogels (B)*. Besides these, there can be (C) photothermal excitation due to the increase in temperature locally, (D) reactive site activation or deactivation, and (E) release or capture of substrates [reprinted with permission from ref. 122, ©John Wiley and Sons, 2019].

electric field responsive hydrogels, for example, poly(2-(acrylamido)-2-methylpropanesulfonic acid) (PAMPS) hydrogels.^{130,133}

ECHs are synthesized by the incorporation of conductive materials (Fig. 9) such as metallic NPs (*e.g.* Au NPs), conductive polymers (*e.g.*, polypyrrole (PPy), polyaniline (PANI), and poly-3,4-ethylene dioxthiophene: PEDOT, *etc.*), and carbon-based materials (*e.g.*, graphene and carbon nanotubes) as fillers into the hydrophilic hydrogel matrix.^{13,134}

The application of ECHs in soft electronics is drawing attention due to their enhanced conductivity, stretchability, and flexibility.^{135,136} These properties are favorable for flexible strain sensors and highly applicable in soft robotics, human-machine interfaces, and micromachines.¹³¹ Biosensors and bioelectronics-based conductive hydrogels for the detection of pathogens,¹³⁷ glucose concentration,¹³⁸ and viruses,¹³⁹ delivering drugs,¹⁴⁰ and environmental monitoring¹⁴⁰ are being developed rapidly.¹⁴¹

4.4. Synthesis of magnetically responsive hydrogels (MRHs)

Usually, magnetic responsive behavior can be imparted by incorporating magnetic NPs (MNPs) as a dispersion in a cross-linked polymeric matrix rendering responsive behavior against magnetic stimuli.¹⁴² With the change of magnetic state, the mechanical, thermal, and acoustic behaviors are also affected simultaneously as the magnetic part behaves as a composite along with the hydrogel matrix.¹⁴³ Due to the inclusion of magnetic NPs, the hydrogel application expands through many areas. Moreover, the optimum effect can be achieved by ensuring the

homogeneous distribution of magnetic NPs to create a hybridized hydrogel composite.^{144,145} Therefore, in the case of magnetic NPs embedded into hydrogels, it is necessary to control the distribution of NPs within the hydrogel network which can be manipulated by creating a magnetic field outside. Furthermore, the properties of such a hydrogel can also be affected by factors like the concentration and size of both the hydrogel and magnetic particles. These magnetic gel types can be synthesized by incorporating NPs that are responsive to a magnetic field into a cross-linked hydrogel network. Mainly, three major synthesis processes are followed to develop a magnetic nanoparticle hybridized hydrogel: the blending method, the encapsulation or co-precipitation method, and the grafting approach (Fig. 10).^{143,146–149}

By comparing hydrogels with randomly distributed MNPs with those incorporating homogeneously distributed MNPs, it is found that the distribution arrangement greatly influences the magnetothermal behavior of hydrogels. Hence, magnetothermal properties can be regulated by controlling the arrangement of MNPs inside the hydrogel *via* the regulation of the magnetic field.^{151–154} To improve the collective magnetic properties of MNPs as well as their monodispersity and homogeneity, they can be assembled into a one-dimensional structure (Fig. 11).^{144,158}

Besides, when MNPs are exposed to an alternating electromagnetic field, the magnetization flip dissipates thermal energy to the surroundings and causes magnetic hyperthermia.^{155,156,162} This phenomenon has been largely used in chemotherapy to kill malignant cells.^{159,160,163,164} There are four major methods for



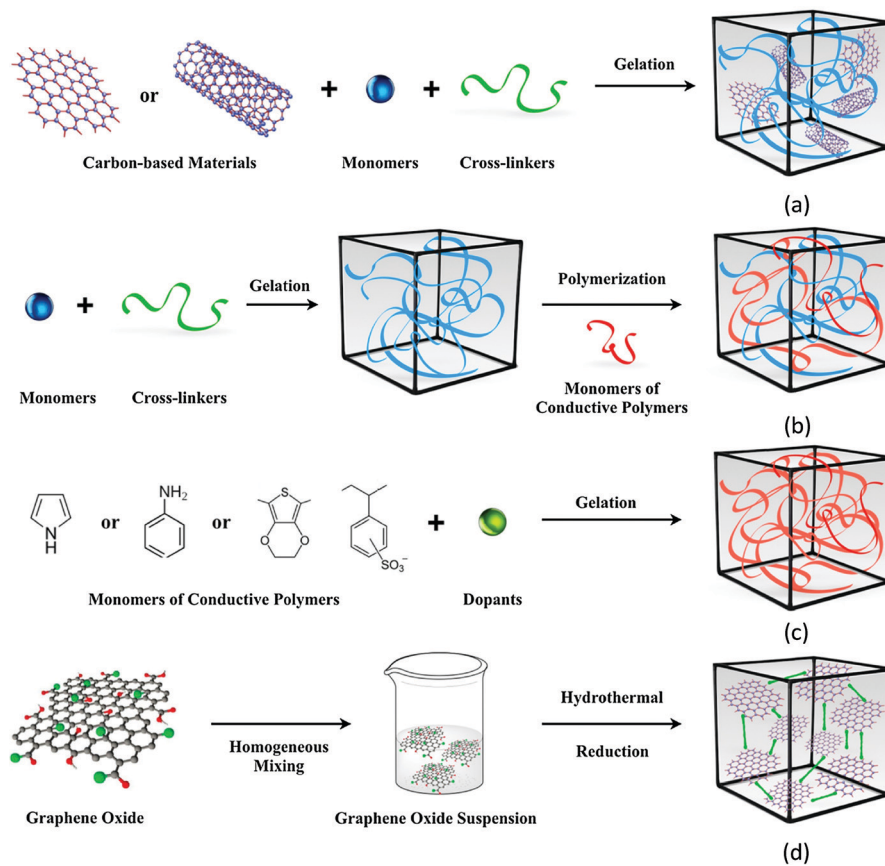


Fig. 9 Four main approaches were used to obtain ECAs. (a) Hydrogel formation from a conductive filler suspension. (b) Polymerization within a preformed hydrogel matrix. (c) Crosslinking conductive polymers by dopant molecules. (d) Self-assembly of a graphene hydrogel via supramolecular interactions [reprinted with permission from ref. 134, ©Elsevier, 2019].

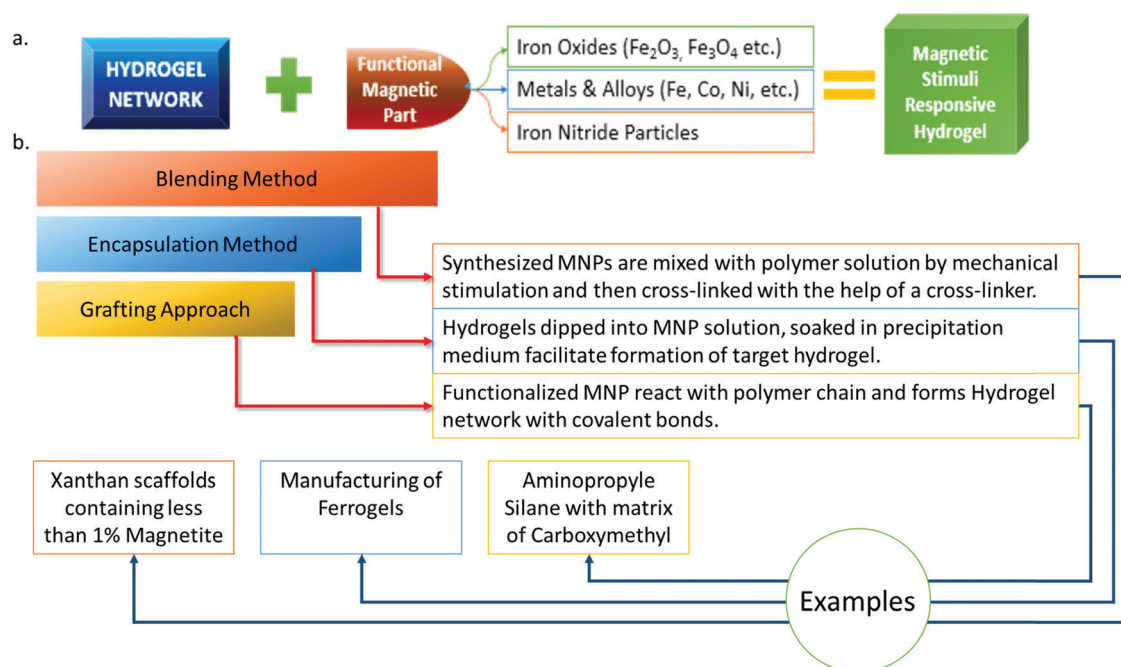


Fig. 10 (a) Principle of magnetically responsive hydrogel synthesis (based on ref. 143). (b) Major synthesis principles of MNP hydrogels with examples (based on ref. 142, 143 and 150–157).



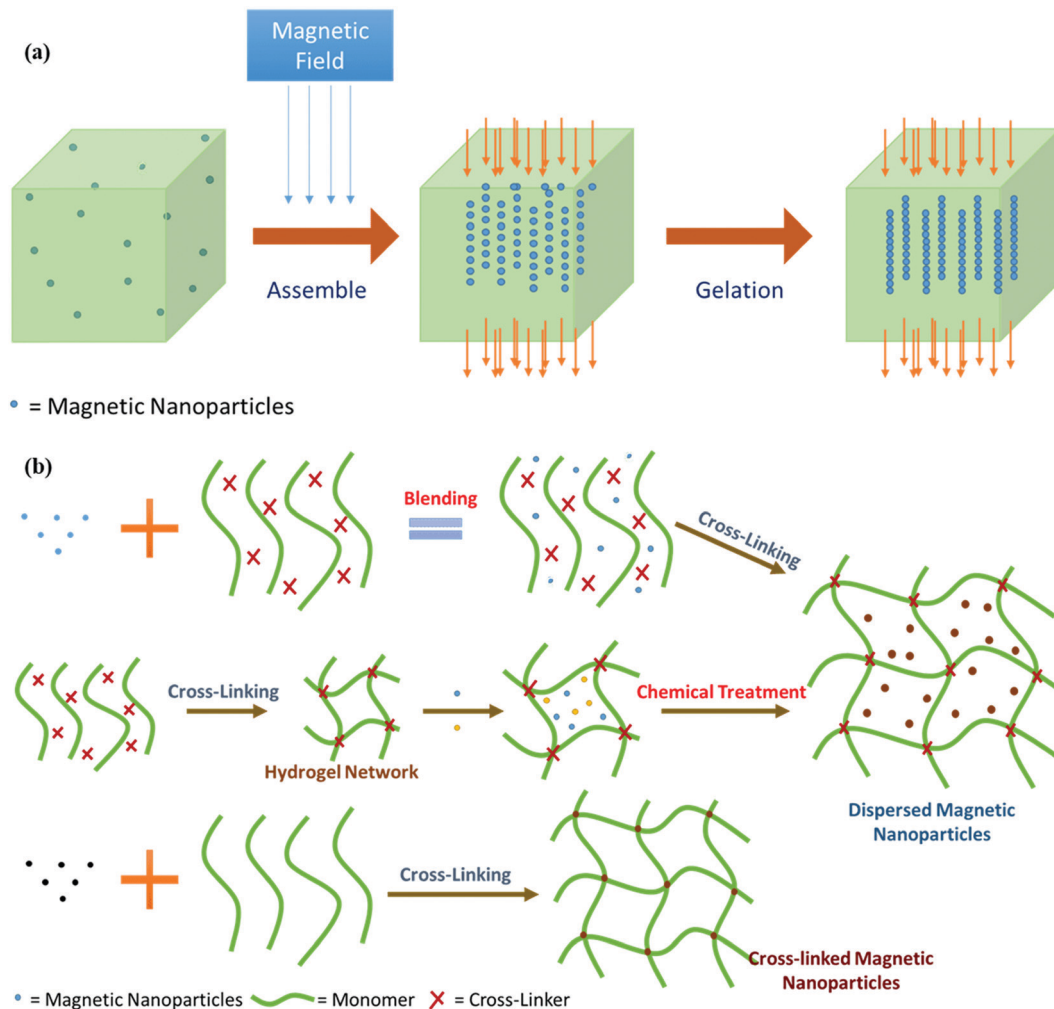


Fig. 11 (a) Effect of magnetic field on MNPs incorporated in the hydrogel [reproduced from ref. 3]. (b) Major preparation methods for synthesizing a magnetic nanoparticle-induced hydrogel and a regenerated nanoparticle-induced hydrogel [reproduced with permission from ref. 146, ©2015 by the authors, open access under attribution 4.0 international (CC BY 4.0)].

the synthesis of magnetic stimulus hydrogels with suspension polymerization (Fig. 12).

4.5. Synthesis of sound responsive hydrogels (SORHs)

Among different environmental stimuli, smart hydrogels are also responsive to sound or ultrasound.^{166,167} Ultrasound refers to the sound beyond the limit of human hearing and has applications in many fields such as cleaning, mixing, and imaging.^{168,169} Particularly in the biomedical field (*e.g.*, drug release, cancer therapy), its applications with hydrogels are prevalent.^{167,170–175} Polymers or hydrogels can be activated and allowed to burst due to their interaction with ultrasound waves, thereby releasing drug loads into specific tissues (Fig. 13a).

SORHs exhibit a reversible de-crosslinking–crosslinking behavior when interacting with sound waves. In the presence of ultrasound, crosslinks break and, conversely, regenerate upon the withdrawal, thus rendering the self-healing ability to SORHs (Fig. 13b). This mechanism can be incorporated to release drugs in a controlled manner.¹⁷⁰

The synthesis of SORHs varies with their application. For example, Zhang *et al.*¹⁷⁷ developed a hydrogel composite with an MXene ($\text{Ti}_3\text{C}_2\text{T}_x$), which was found to be successful in monitoring the phonatory process or sound of the human voice. MXene ($\text{Ti}_3\text{C}_2\text{T}_x$) nanosheets with PVA, water, and anti-dehydration agents were combined to fabricate this hydrogel.

Kwok *et al.*¹⁷⁸ synthesized a SORH to facilitate on-demand drug release. They developed a methylene chain within the drug insulin polymer to produce the final ultrasound responsive hydrogel. Crosslinked hydrogel slabs were made *via* copolymerization of the monomer HEMA, 2-hydroxyethyl acrylate (HEA), poly(ethylene glycol) dimethacrylate (PEGDMA), and insulin. PEG was incorporated to form large pores so that the hydrogel can retain large protein molecules like insulin. Then the methylene chains were developed over the PHEMA surface by processing it with C-12 isocyanate, dibutyltin dilaurate (catalyst), and anhydrous tetrahydrofuran.^{178,179} Exposure of ultrasound to this insulin drug-containing hydrogel showed successful sound controlled drug release.¹⁷⁸



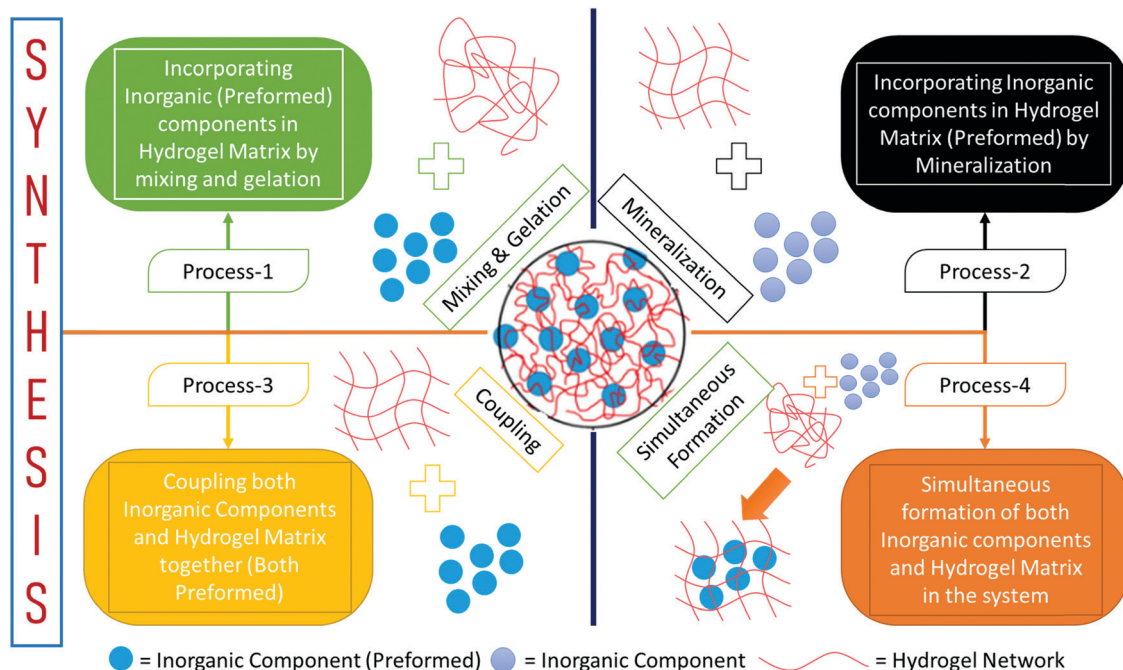


Fig. 12 Major synthesis processes of magnetic stimulus hydrogels with suspension polymerization (based on ref. 147 and 161–165).

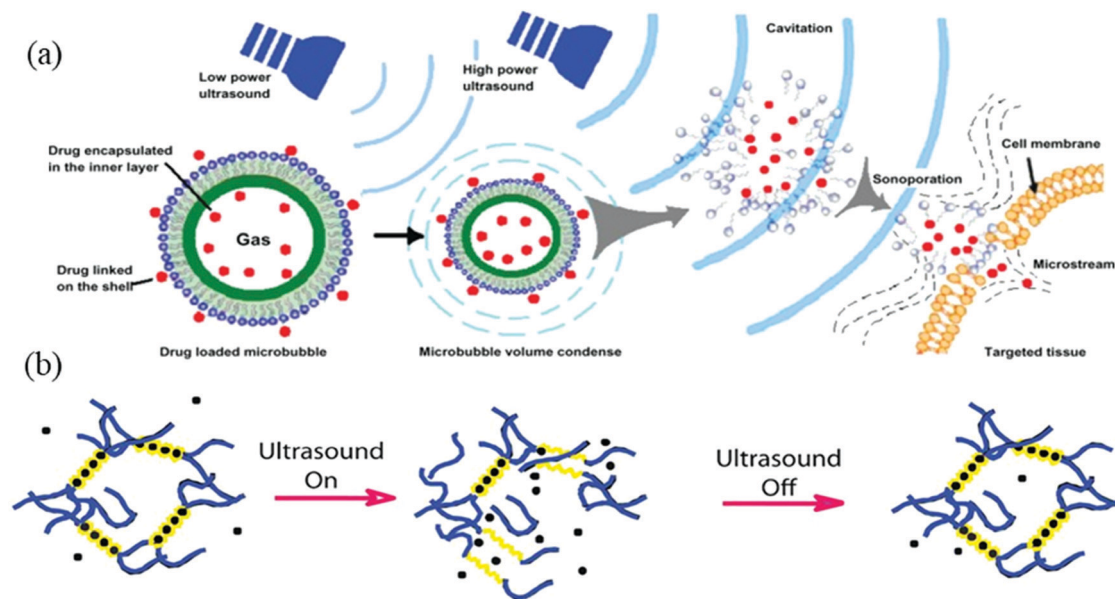


Fig. 13 (a) Schematic diagram of the working principle of low and high ultrasound on polymers for drug release [reprinted with permission from ref. 176, ©Dovepress, 2013]. (b) Disruption and self-healing of an ultrasound responsive ionic cross-linked hydrogel [reprinted with permission from ref. 170, ©PNAS, 2014].

4.6. Synthesis of pressure responsive hydrogels (PRHs)

The ability of hydrogels to detect the pressure exerted on them and exhibit various responses under various pressures is a novel characteristic. This behavior is apparent in super-elastic, cellular structured, and nanofibrous hydrogels, for example, hydrogels produced by the combination of alginate and flexible SiO₂ nanofibers. Hydrogels with an ultrahigh water content (above 97%) do not exhibit robust mechanical strength and significant recoverable

deformation because of containing a high amount of water. These hydrogels are formed by assembling different polymer units, such as proteins, NPs, polysaccharides, polyelectrolytes, and so on, into 3D networks. Although they have a homogeneous distribution of networks, they tend to lose mechanical properties in a high water-containing environment. In such a case, hydrogels of cellular fibrous networks can readily improve mechanical properties and exhibit a significant response when pressure is applied.^{180–184}



Respective swelling/shrinkage and expansion/contraction are apparent upon the application of external pressure on hydrogels containing large mono-domains. A study reports the incorporation of a mechanical shearing technique for synthesizing half ester nanocrystallized cellulose (CNC). This includes UV-triggered polymerization of a monodomain anisotropic gel converted by shearing. When subjected to pressure between cross-polarizers, this hydrogel displays rapid and reversible color changes, accompanied by the degree of alignment observed as swelling.^{185,186}

In another study, a SiO₂ nanofibrous hydrogel was synthesized by incorporating four elements, namely, water, alginate, SiO₂ nanofibers, and a metallic cation (Al³⁺), by applying the sol-gel electrospinning technique.¹⁸⁷ The pressure-responsive characteristics can be readily used for different advancements in the field of hydrogels such as flexible pressure sensors, tissue-engineered scaffolds within the range of pressure stimulus, drug delivery vehicles, artificial skin, and bio-actuators, to name a few.¹⁸⁰

4.7. Synthesis of pH-responsive hydrogels (pHRHs)

pH-Responsive hydrogels are generally synthesized by utilizing polymers constructed using monomers containing ionizable pendant/functional groups of -OH, -COOH, -NH₂, -CONH₂, -N<, and -SO₃H.^{12,48,188,189} When such a hydrogel is exposed to a solvent (e.g., aqueous solution) of certain pH and ionic strength, its pendant/functional groups will get ionized with fixed charges and these charges will exhibit electrostatic repulsion, resulting in a reversible swelling-deswelling mechanism depending on the acidic or basic nature of the medium.⁴⁸ The presence of anionic and cationic pendant groups in polymers influences pH depending on the swelling behavior of the hydrogels. Hydrogels with cationic pendant groups [e.g. CHT, poly(*N,N*-dimethylaminoethyl methacrylate) (PDMAEMA), and poly(*N,N*-diethylaminoethyl methacrylate) (PDEAEMA)] swell at pH < pK_a and deswell at pH > pK_a (Fig. 14a), whereas hydrogels with anionic pendant groups (e.g. albumin and PAAc) swell at pH > pK_a and

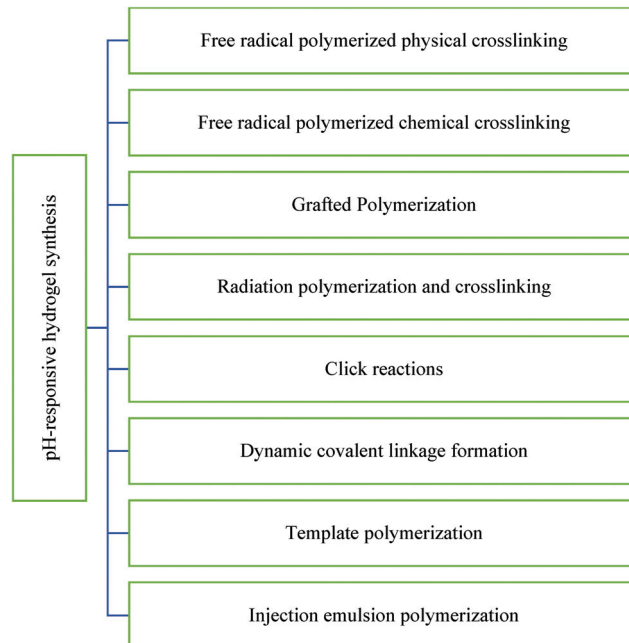


Fig. 15 Major approaches to synthesize pH-responsive hydrogels (based on ref. 9, 188 and 193–200).

deswell at pH < pK_a (Fig. 14b).^{48,190,191} Both synthetic and natural polymers with ionizable functional groups can be utilized to synthesize hydrogels with pH-responsive behaviors.⁴⁸ This pH-stimulated reversible shrinkage-expansion mechanism of hydrogels is utilized to deliver therapeutic drugs protectively.¹⁹²

Numerous approaches can be adopted to synthesize pH-responsive hydrogels such as free radical polymerized chemical crosslinking,¹⁸⁸ free radical polymerized physical crosslinking,¹⁹³ grafted polymerization,¹⁹⁴ injection emulsion polymerization,⁹ radiation polymerization and crosslinking techniques,¹⁹⁵ template polymerization,¹⁹⁶ covalent linkages,^{197,198} click reactions,¹⁹⁹ etc. The major advantage of these hydrogels is their capability to administer drugs (especially protein and peptide-based drugs) orally while protecting them through the gastrointestinal tract (Fig. 15).¹⁹³

Hibbins *et al.* developed a novel drug delivering pH-responsive hydro-porous hydrogel based on *in situ* free-radical copolymerization of the monomers AAm and methacrylic acid with MBAAm as the chemical crosslinking agent.¹⁸⁸ Similar polymerization and crosslinking approaches were utilized by Shantha and Harding to fabricate pH-responsive hydrogels of *N*-vinylpyrrolidone (NVP), PEG diacrylate, and chitosan, where the -NH₂ groups of chitosan were able to ionize in acidic medium (pH 1.2). A combined process of graft polymerization and free radical polymerized chemical crosslinking was applied to synthesize dual responsive hydrogels (*i.e.* pH and temperature) by grafting cellulose nanowhiskers onto AAm (CNWs/AAm); afterward, CNWs/AAm was polymerized with NIPAAm in the presence of MBAAm crosslinkers to obtain the final hydrogels.¹⁹⁴ Hydrogels based on the physical interactions of AAC and 2-(dimethylamino) ethyl methacrylate (DMAEMA) copolymers developed *via* free radical polymerization were also studied by Suhag *et al.*¹⁹³

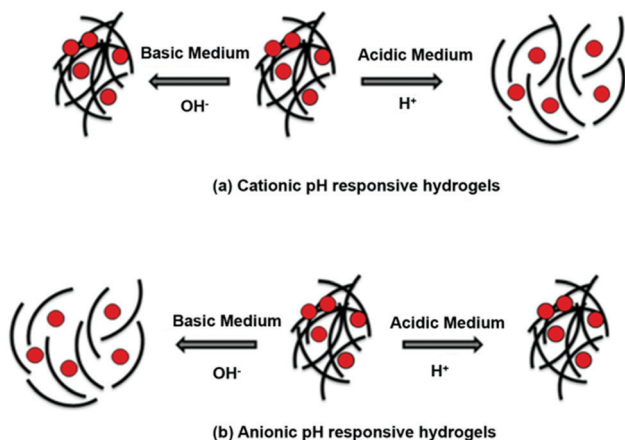


Fig. 14 The schematic representation of pH-responsive hydrogels. (a) Cationic hydrogels swell at low pH and deswell at high pH. (b) Anionic hydrogels swell at high pH and deswell at low pH [reprinted with permission from ref. 190, ©2019 by the authors, open access under attribution 4.0 international (CC BY 4.0)].



Hydrogels obtained through γ -irradiation initiated copolymerization and the crosslinking approach were reported to be more advantageous than those obtained *via* chemically initiated polymerization and crosslinking due to the exclusion of additives (*i.e.* initiators and crosslinkers). This approach produces sterilized hydrogels of non-carcinogenesis. Hydrogels of AAc and DMAEMA obtained *via* the radiation technique were reported and simulations were carried out in a buffer solution to study ketoprofen drug delivery in the colon. Most importantly, template polymerization can be performed to overcome the disadvantages of reduced bioactivity and inhomogeneity of chemically and physically crosslinked hydrogels, respectively.¹⁹⁶ pH-responsive hydrogels *via* template polymerization of PAAc and DMAEMA can facilitate the immobilization of an enzyme (*i.e.* β -galactosidase).¹⁹⁶

4.8. Synthesis of redox responsive hydrogels (RRHs)

SRHs have been developed with the ability to sense reactive oxygen species (ROS), which facilitate cell protection against oxidative stress. These SRHs, herein designated as RRHs, can sense and eliminate the ROS produced from cellular metabolism. ROS are highly reactive reagents and abundantly present in the human body. They play a significant role in cell signaling pathways but cause strong oxidative degradation to liquids, proteins, nucleic acids, *etc.*^{201,202} As a result, excessive ROS generation disrupts body functions and is responsible for systemic diseases.^{203–208} When a redox-responsive hydrogel is mixed with an oxidant (*e.g.* NaClO), its viscosity reduces and a transition into a solution phase occurs; on the contrary, when a reductant (*e.g.* glutathione (GSH)) is added to this solution, its viscosity increases and gelation occurs. This concept is applied to mitigate the effect of ROS. A similar mechanism was also observed through electrochemically-induced redox reactions (Fig. 16).^{204,209}

A synthesis process of such a redox responsive hydrogel includes the incorporation of redox-sensitive entities into a temperature-responsive environment during fabrication. A study reports that the functionalization of a copolymer fabricated by ring-opening polymerization can be done *via* a thiol-yne reaction to incorporate the redox-sensitive characteristic in the hydrogel. Under the stimuli of chemicals like H₂O₂, the resulting copolymer can show redox-sensitivity.²⁰⁴ The inclusion of redox-sensitive organo-metallic compounds can also be applied to synthesize RRHs. For example, Nakahata *et al.* developed a hydrogel based on host (PAAc/ β -CD)-guest (PAAc/FE) polymer chemistry by integrating redox-sensitive ferrocene (FE) with PAAc.²⁰⁹ According to another concept, disulphide linkage-based crosslinking is one of the popular approaches to fabricate redox-sensitive hydrogels based on thiol-disulphide exchange reactions.¹⁰

4.9. Synthesis of glucose-responsive hydrogels (GRHs)

Modern research into stimulus-responsive hydrogels has opened a new dimension towards advancements that were beyond imagination once. One of the most widespread and commercialized studies involves the synthesis of glucose-responsive hydrogels. These hydrogels can be very popularly used in advanced science such as self-monitoring of blood glucose (SMBG) to regulate the blood glucose level of diabetic patients,^{210,211} and as effective insulin and

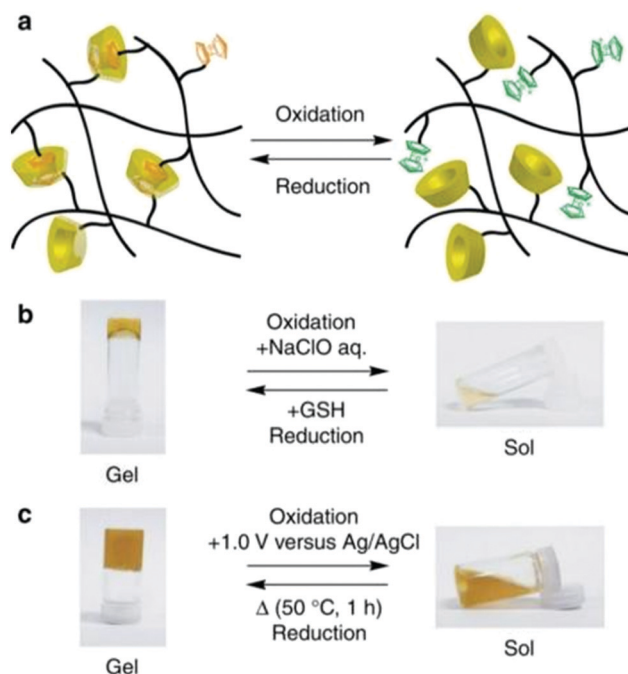


Fig. 16 Redox-responsive sol-gel transition. (a) Schematic illustration of sol-gel transition. (b) Sol-gel transition against chemical reagents (NaClO and glutathione). (c) Electrochemical oxidation (+1.0 V versus Ag/AgCl) and reduction induced sol-gel transition [reprinted with permission from ref. 209, ©Springer Nature, 2011].

drug carriers. They can also be applied in the form of nanogels, microgels, micelles, vesicles, mesoporous NPs, *etc.*²¹² One of the popular synthetic methods is based on dynamic covalent linkages. A study shows that the PEO-*b*-PVP diblock polymer, α -cyclodextrin (α -CD), and phenylboronic acid (PBA)-terminated PEO crosslinker can simply be mixed to form a hydrogel solution. While PVA and PBA together form the crosslinker required, the inclusion occurs between PEO and α -CD. This reaction is responsible for both hydrogel formation and providing necessary stability. The hydrogel structure tends to dissolve in the presence of glucose and thus can be very effective to release loaded drug proteins in the intended environment (Fig. 17).²¹³

In another study, free radical copolymerization has been employed for producing other GRHs. Preparing a stock solution of AAm and MBAAm in 4-(2-hydroxyethyl) piperazine-1-ethane sulfonic acid (HEPES) is the first step, followed by mixing *N*-(3-dimethyl aminopropyl acrylamide) (DMAA) and *N,N,N',N'*-tetramethylethylenediamine (TEMED) with the solution. Herein, 3-acrylamidophenylboronic acid (3-APB) acts as a free radical initiator. Free-radical crosslinking takes place in the solution and thus GRHs are produced. After confining the resulting hydrogel into a porous membrane, when a change in the concentration of glucose around it is brought, a transition is observed. The hydrogel senses the glucose stimulation through the porous structure.^{214,215}

4.10. Synthesis of CO₂ responsive hydrogels (CO₂RRHs)

The surface properties of CO₂-responsive hydrogels are controllable with the stimulation of CO₂. In most cases, the modification



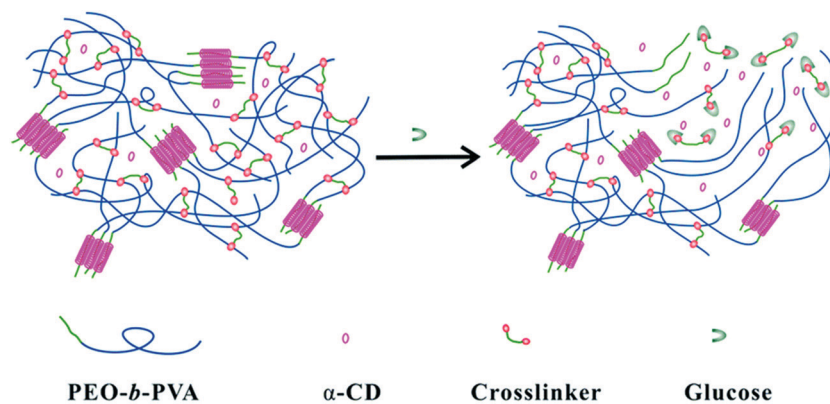


Fig. 17 Schematic illustration of the glucose response mechanism of the hydrogel formed with PEO-*b*-PVA, α -CD, and a cross-linker [reprinted with permission from ref. 213, ©The Royal Society of Chemistry, 2014].

comes in the form of a reversible switching technique.²¹⁶ In one-way CO₂ stimuli-responsive hydrogels can be prepared by cross-linking the gels with discrete metal-organic macrocycles (MOM) or metal-organic cages (MOC). This technique has added a new magnitude of versatility in the field of supramolecular self-assembled hydrogels.

In one study, a new family of star block copolymers (SBCP) prepared with MOM as the core show CO₂ responsive behavior including CO₂ triggered morphology transition, CO₂ promoted hydrogel formation, and even CO₂-induced thermo-responsive behavior. Moreover, the bubbling of N₂ results in a hydrogel with a reverse sol-to-gel transition.^{217–226} Such CO₂ responsive hydrogels have found applications in different sectors such as CO₂ capture and monitoring, separation, encapsulation, and CO₂ switchable vesicles.^{227–232} The reversible swelling-deswelling property in the presence of a green stimulus like CO₂ is a topic of interest where external stimulation can be used to exhibit responsiveness (Fig. 18).^{233–238}

In addition to CO₂ responsive hydrogels, CO₂-temperature dual stimuli-responsive hydrogels can be conveniently used in various circumstances and showed significant potential in

targeted drug transport and controlled drug release. Lie *et al.* synthesized a CO₂-temperature-responsive hydrogel from PDMAEMA with a β -CD *via* atom transfer radical polymerization (ATRP). This supramolecular triblock stimuli-responsive copolymer exhibits good biocompatibility with PNIPAAm and PDMAEMA hydrophilic segments and polycaprolactone (PCL) hydrophobic segments. The resultant triblock copolymer is responsive to carbon dioxide (CO₂) gas and temperature reversibly through self-assembly into cell vesicles.²³⁹

4.11. Synthesis of enzyme responsive hydrogels (EZRHS)

Since all the major changes occurring in living cells are because of enzymes, in the field of artificial materials enzymes are being used as a trigger to create biomimetic responsive materials. These include hydrogels that not only undergo structural changes but also interact with the environmental components upon exposure to different enzymes.^{36–40} To synthesize novel responsive polymers, enzyme and enzyme-catalyzed reactions have turned out to be potential triggering elements.^{38,240,241} Enzymes are biological substances that act as a natural trigger. Since enzymes are biomolecules, it is possible to release as per

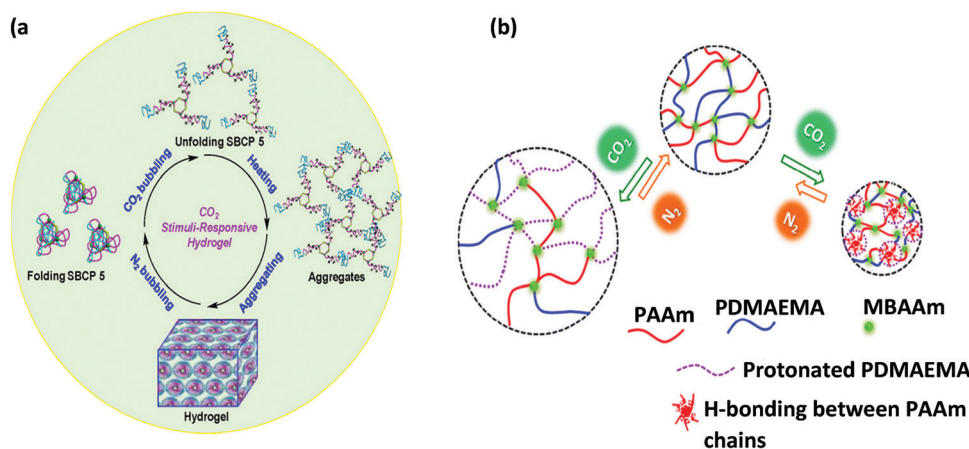


Fig. 18 (a) Schematic illustration of a CO₂ responsive hydrogel of a star supramolecular block copolymer (SBCP) [reprinted with permission from ref. 217, ©American Chemical Society, 2017]. (b) Schematic illustration of CO₂ switchable swelling behaviors of P(AAm-co-DMAEMA) hydrogels [reprinted with permission from ref. 233, ©Springer Nature, 2018].



requirement wherever necessary by controlling physical attributes and harmonizing the material response.²⁴² Enzyme responsive hydrogels with low molecular weight gelators (LMWG) are recent developments in this field as the enzymatic process involves adaptation and reorganization of the gel surface.^{36,243}

For the synthesis of EZRHs, one of the most popular techniques is the incorporation of an enzyme-catalyzed reaction. Here, an enzyme acts as a key biological catalyst capable of bringing about chemical or morphological changes within hydrogel cells. It can be used to obtain enzyme-mediated bio-responses, especially in the biomedical field. To synthesize such EZRHs, there are mainly three basic requirements. The hydrogel must contain embedded enzyme recognition elements like linkers. Next, the linkers must be accessible by the enzyme to ensure the enzyme-catalyzed reaction. Finally, the enzyme linker reaction imparts physical or chemical changes, *i.e.* degradation or morphological transitions.^{242,244,245}

Another concept is that some hydrogels can release trapped biomaterials in the presence of an enzyme. This is possible due to the disintegration of hydrogel-forming polymer chains. Hydrogels with such characteristics can be synthesized in two ways: firstly, by a simple covalently cross-linked network of the normal polymer and secondly in the form of a supramolecular structure that takes place among multiple self-assembling molecules (hydrogelators). The hydrogelators interact to form nanofiber structures. The intermingling of these nanofiber structures is responsible for forming a hydrogel network in this way.^{243,246–248}

The graphical illustration (Fig. 19) shows the action of the hydrogels in the presence of an enzyme. The hydrogel contains a linkage itself which links with the provided enzyme and brings about morphological changes in the hydrogel structure. This is applicable in both the intracellular cytoskeleton and extracellular matrices (ECM). This is an example of bio-simulation or bioactivation.^{243,249,250}

Generally, the chemical synthesis process of a hydrogel includes covalent cross-linking among polymer chains. The formation of the hydrogel is done *via* two principal steps. Initially, the biodegradable component is dissolved into a liquid state.^{84,251,252} The physical hydrogel can be produced by ensuring physical interactions or

cross-linking among biological components. As we know, some enzyme-responsive polymers typically contain enzyme reactive groups either in their main chain or as additional side groups. They exist in the form of labile linkages. These linkages cause modification and tuning of the transformation in the structure *via* different non-covalent interactions triggered by enzymes.^{84,241} Some of the physical networking processes are shown in Fig. 20.

Enzymes are specific in their actions and activated by hydrogel degradation. They are absorbed as biocatalysts to regulate the controlled release of drugs and biomolecules at desired locations. For a polymer to be enzyme responsive, some conditions must be met; for instance, an enzyme responsive substrate, a compound having a high influence on the kinetics of the enzyme–catalyst interaction. Finally, the enzyme–substrate reaction requires altering the material properties.²⁵⁴ Enzymatic action on the substrate as a consequence of the molecular interaction in terms of forming different chemical bonds such as hydrogen bonds, electrostatic interactions, van der Waals interactions, hydrophobic interactions, π - π interactions, or any other combination of these bonds triggers the alteration of these surface properties (supramolecular architectures, self-assembly and swelling/shrinkage of hydrogels).²⁵⁵ A study shows the incorporation of urea and rhodamine 6G (RH6G) to formulate a urea-based hydrogel that demonstrates a typical sol-to-gel phase transition due to enzymatic hydrolysis in the presence of the enzyme β -galactosidase (β -Gal).²⁵⁶ Another study reports a hydrogel formed of covalent cross-linking between the β -(1 \rightarrow 4) linked D-glucose unit and chitin which can be incorporated for targeted medication release in response to 2-acetamido-2-deoxy- β -D-glucose.⁸⁴

4.12. Synthesis of antigen responsive hydrogels (ARHs)

Antigen responsive hydrogels exhibit a volume or mass transition in the presence of an antibody or its supplementary. Physical entrapment of the antigen in the hydrogel network, chemical conjugation of the antigen, and the utilization of the antibody–antigen pair as a reversible cross-linker are usually employed to fabricate them with great potential for application in biosensors.^{14,41}

In the field of supramolecular hydrogels, it is possible to prepare an antigen-responsive structure. LMWG can be manipulated to exert self-assembly to construct supramolecular

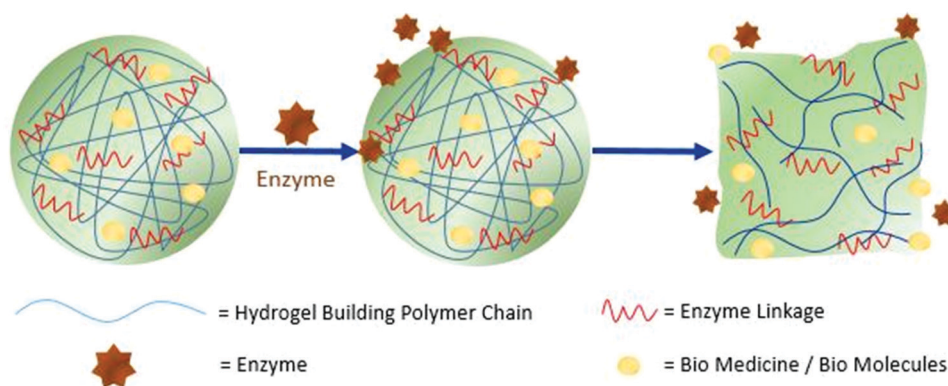


Fig. 19 Hydrogel responding to the enzyme and mechanism to release biomolecules [reproduced with permission from ref. 242, ©SAGE Publications, 2016].



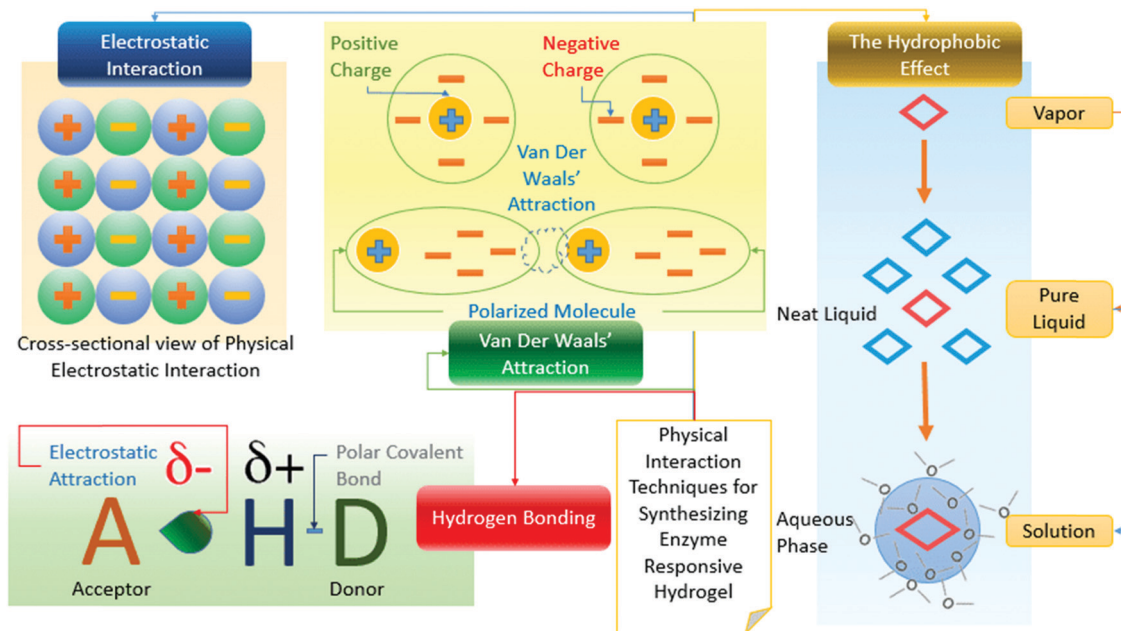


Fig. 20 Physical interaction processes for producing enzyme responsive hydrogels (based on ref. 84, 241 and 253).

hydrogels. The stability of a supramolecular hydrogel capsule in a cell culture medium allows it to further upgrade to an enzyme and a cell responsive hydrogel, which possesses an appropriate mechanism to release fluorescent drugs stimulated by prostate specific antigen (PS)-catalyzed proteolysis. It has good potential for application in the diagnosis of prostate cancer.^{15,257–260}

A hydrogel-based smart membrane can be produced by grafting the dextran backbone in a fluorescein isothiocyanate (FITC) antigen and a sheep anti-FITC IgG antibody where the bio-specific interactions between IgG and FITC ensure additional stabilization of the structure.²⁶¹ A recent study demonstrates the synthesis of a hydrogel from the copolymerization of IgG2a and NIPAAm through redox initiation and chemical crosslinking *via* MBAAm.¹⁴ Using a similar mechanism of change in their crosslinking density in response to target molecules, a target responsive hydrogel can be engineered.¹⁶ This novel hydrogel shows great potential for quantitative point-of-care testing with higher sensitivity and accuracy in detecting cocaine, ochratoxin A, and lead ions. The hydrogel was constructed as described in earlier studies^{262–264} with DNA grafted linear PAAM and cross-linking DNA for targeted recognition. The mechanism of this action is presented in Fig. 21. The hydrogel was formed upon the hybridization of polymer strands and linker DNA (aptamer or DNAzyme). The hydrogel response to the target substance allows the release of the pre-loaded Pt NPs, which have good stability and excellent catalytic ability for decomposing H_2O_2 to O_2 . Then, the generated O_2 in an enclosed environment leads to a significant pressure increase, which is rapidly traceable by a pressure meter (Table 2).²⁶⁵

The list of recently developed major stimuli-responsive hydrogels is given below.

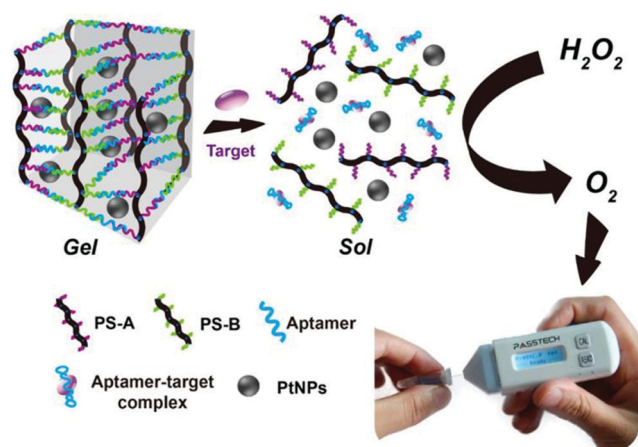


Fig. 21 Working principle of the target-responsive hydrogel pressure-based assay [reprinted with permission from ref. 265, ©American Chemical Society, 2017].

5. Synthesis of hydrogels for targeted applications

Functional hydrogels are programmed by surface modifications that can partly endow hydrogels with desired properties while retaining the original intrinsic physicochemical properties of the hydrogel network. This surface functionalization is considered as an alternative strategy for the fabrication of multifunctional hydrogels for targeted applications.^{303,304} Functionalization of the surfaces of hydrogels can be done in three ways: the construction of a surface structure, physical incorporation of functional micro/nanomaterials, and chemical grafting.^{127,305–313}

The properties of hydrogels are easily tunable by modifying functional groups³¹⁴ and incorporating functional materials.^{315–317}



Table 2 Recently developed temperature, light, electricity, and pH-responsive hydrogels

Responsive to	Synthesis technique	Crosslinking method	Main materials	Application area	Ref.
Temperature	IPN method Grafting	Chemical crosslinking Physical crosslinking	PAAc-g-β-CD and PAAM Xyloglucan and xyloglucan/pectin	Drug delivery Oral drug delivery	266 96 and 267
	PEO/PPO block copolymerization	N/A	PO and EO	Biomedical engineering	268
	Atom transfer radical polymerization	Covalent crosslinking	PCL, NIPAAm, HEMA, DBA, and Me ₆ TREN	Myocardial injection	269
	Radiation polymerization Graft copolymerization	Chemical cross-linking Chemical cross-linking	PNVCL Phenolated alkali lignin, NIPAAm	Drug release Tissue repair, drug release, and water purification	270 271
	Full-IPN hydrogels	Chemical cross-linking	NIPAAm and Na-Alg	Biomedical engineering	272
	Surfactant-free emulsion polymerization (SFEP)	Covalently crosslinking	NIPAAm, AAC, and Au NPs	Drug delivery	124
	Branched copolymerization and dissolution	Crosslinking <i>via</i> a supramolecular complex	Deoxycholate-β-CD and (AzBPAAC)	Light controlled encapsulation or release of molecular and cellular species	125
	Photopolymerization in dispersion	Chemical crosslinking <i>via</i> MBAAM	GO, GMA, NIPAAm, and DMSO	Microelectromechanical systems, microfluidic devices, and lab on chips	126
	Dissolution, mixing, and gelation	Physical crosslinking	PPy NPs, agarose, and alginate	Biological applications	121
	Photopolymerized chemical crosslinking	Crosslinking <i>via</i> MBAAM	NIPAAm, AAC, and spiropyrans	Microfluidic devices	123
Electricity	Photo-initiated free radical polymerization and physical cross-linking or chemical crosslinking	Crosslinked by AH NPs or MBAAM chemical crosslinking	AAC and DMAAM	Sensors, actuators, switches, and artificial muscles	273
	MFS and photo-initiated polymerization and chemical crosslinking	Chemical crosslinking by MBA	GO, AAm, Na-Alg, and CaCl ₂	Artificial muscle actuators	274
	<i>In situ</i> free-radical polymerization and chemical crosslinking	Chemical crosslinking by the macro-crosslinker PF127DA	AAm & AMPS	Sensors, actuators, switches, and artificial muscles	275
	Photo-initiated free radical polymerization and chemical crosslinking	Chemical crosslinking by MBAAM	AAm, 98% PBA, DMSO, and 97% HMPP	Glucose monitoring	276
	TEMPO-laccase catalytic redox system reaction	Dynamic imine bonds (<i>i.e.</i> Schiff base reaction)	Chitosan (CHT)	Medicine and food	277
	Photo-initiated free radical polymerized chemical crosslinking	Crosslinking by the macro-crosslinker MA-PLLA-PEG-PLLA-MA	MA-PLLA-PEG-PLLA-MA, AAC and NIPAAm	Drug delivery, oral drug administration, and antimicrobial	278
	Dissolution & chemical crosslinking	Chemical crosslinking by glutaraldehyde	CHT, PVA, and humic acid (HA)	Biotechnological applications and drug delivery systems	279
	Free radical polymerized chemical crosslinking	Chemical crosslinking by a macro-crosslinker (MLS)	NIPAAm, itaconic acid (IA)	Release of pesticides or drugs	280
	Dissolution & chemical crosslinking	Schiff base reaction	Chitosan, dihydrocaffeic acid (DA), and oxidized pullulan (OP)	Mucoadhesive drug delivery systems and antimicrobial	281
	Photo-initiated free radical polymerized chemical crosslinking	Chemical crosslinking by MBAAM in PAAc and physical crosslinking in PVA	PAAc, gelatin powder, and PVA	Medical transplantation, tissue engineering, and sensor technology	282
Free radical polymerized physical crosslinking	Physical crosslinking	AAC and DMAEMA	Drug release and biomedical industry	193	
Magnet	Spontaneous localization at the interface of magnetic particles	Self-assembly of inorganic colloidal particles at a liquid-liquid interface	Iron oxide (Fe ₂ O ₃), NIPAAm, and AAM	A delivery system for biomolecules, drugs, food supplements, cosmetics, living cells, <i>etc.</i>	161
	Hybrid hollow spheres by infiltration with a TiO ₂ precursor	Organic-inorganic hybrid hollow sphere hydrogel	TiO ₂ , polystyrene	Drug release system, containers for catalyst components	283



Table 2 (continued)

Responsive to	Synthesis technique	Crosslinking method	Main materials	Application area	Ref.
	A one-pot methodology for developing a hemicellulose-based hydrogel by covalent cross-linking Magnetic nanoparticles incorporated as a multi-functional cross-linker	Hemicellulose-based hydrogel	Fe ₃ O ₄ , magnetic nanoparticles, TiO ₂ -co-pectin, AcGGM, Fe ₃ O ₄ , FeCl ₃ , FeCl ₃ -6H ₂ O	Biomedical field of tissue engineering applications, controlled drug delivery, magnetically assisted bioseparation	284
		A ferrohydrogel synthesized from magnetic nanoparticles and the PAAM hydrogel network	Siloxane-based unsaturated methacrylic group, CoFe ₂ O ₄ , PAAM	Soft actuators, separation devices, etc.	285
Sound	Membrane emulsification method followed to prepare the drug and then an amidation reaction to form the hydrogel patch Cross-linking process	Four-armed PEG-based hydrogel patches containing diclofenac sodium (DS) loaded polyester microcapsules	DS, PEG- <i>b</i> -PLGA, PBS, 4-arm PEG-NH ₂ and 4-arm PEG-NHS	Transdermal drug delivery	286
		Crosslinked alginate hydrogels	Alginate polymer, calcium sulfate	Cancer therapies, drug release with potential therapeutic benefits	287
		Multilayer hydrogel microcapsules	DNA loaded calcium carbonate, PEI, PMAAc, PNVP, EDC, EDTA	Nucleic acid drug release. Also, the developed hydrogel can be applied for controlled delivery of sensitive biomolecules, as a carrier for DNA vaccines, and in cancer or tissue generation therapies	288
	Mixing of drug and PVA, followed by freezing Cross-linking copolymerization	Composite hydrogel	PVA, silicone oil, Teflon mold	Hydrophobic drug release	289
	N ₂ atmosphere, precipitation, centrifugation, and decantation	Supramolecular polymeric hydrogels	PEG, NHS-activated carboxylic acid group and amine group-modified β-CD, anhydrous DMF	Controlled and accelerated release of large drug molecules	290
	Block copolymerization	Injectable thermoresponsive biocompatible hydrogels	D,L-Lactide and glycolide, methoxy-PEG (mPEG), tin(II) 2-ethyl hexanoate, dry toluene. PLGA, DMSO	Protein drug release	291
Glucose	Reversible covalent interaction	Shear-thinning and self-healing glucose-responsive hydrogels	Phenylboronic acid (PBA), <i>cis</i> -diols, PEG, hexafluorophosphate benzotriazole tetramethyl uronium (HBTU) activated 4-carboxy-3-fluorophenylboronic acid (FPBA) or 4-carboxyphenylboronic acid (PBA)	One-week controlled drug release	292
		Boronate gel-based insulin delivery hydrogel	PBA derivatives, 1,2 or 1,3- <i>cis</i> -diols	Delivery of protein therapeutics, 3D cell culture substrate, biocompatible substance, etc.	293 and 294
	Complex formation between PBA and diols Incubation of glucose/galactose binding protein in the acrylamide hydrogel network Copolymerization of a glucose-responsive monomer with the main monomer	Glucose-responsive hydrogel network based on protein recognition Glucose-responsive hydrogel with a semiconductor-based field-effect transistor (FET)	Glucose/galactose binding protein (GBP), AAm HEMA and vinylphenylboronic acid (VPBA)	Artificial pancreas, non-electric insulin delivery system Controlled drug delivery, implantable drug delivery system	295
Enzyme	Entrapping cationic organic substances within a supramolecular amphiphilic urea-based hydrogel Incorporation of modified gelatin, a cleavable protease sequence, and hyaluronic acid (HA) into a cell-laden gel network	Gel-to-sol phase transition-based hydrogel due to enzymatic hydrolysis Dynamic gelatin-hyaluronic acid (HyA) hybrid hydrogel	Urea, rhodamine 6G (RH6G), β-galactosidase (β-Gal) Gelatin, carbic anhydride, high purity alumina (HPA)	Biosensor for eye contact lens, sheets adhering to the skin, etc. Carrier for cationic biomaterials and dyes 3D cell culture platforms, tumor microenvironment, activation of pancreatic stellate cells	210 256 297–301



Table 2 (continued)

Responsive to	Synthesis technique	Crosslinking method	Main materials	Application area	Ref.
	Covalent cross-linking between cellulose and chitin	Covalently cross-linked hydrogel prepared <i>via</i> dissolution or gelation	β -(1 \rightarrow 4) linked D-glucose unit, chitin, 2-acetamid-2-deoxy- β -D-glucose	Drug delivery (controlled release and targeted release), tissue engineering, wound dressing, water purification, supporting materials for functional additives, thermal insulators, <i>etc.</i>	84
	GOx-mediated radical initiation and polymerization technique	Enzyme-mediated radical polymerized bioactive hydrogel	Glucose oxidase (GOx), β -D-glucose, Fe ²⁺ , N-hydroxyamide compound, N-hydroxy-5-norbornene-2,3-dicarboximide (HONB)	Cell-specific drug delivery, drug carrier	302

Abbreviations (temperature responsive hydrogels): poly(acrylic acid)/*g*/*g*/*f*/ β -cyclodextrin (PAAc-g- β -CD); and polyacrylamide (PAAm); ammonium persulfate (APS); poly(propylene oxide) (PPO); poly(ethylene oxide) (PEO); polycaprolactone (PCL); N-isopropylacrylamide (NIPAAm); 2-hydroxyethyl methacrylate (HEMA); dimethyl- γ -butyrolactone acrylate (DBA); tris(2-(dimethylamino)ethyl) amine (Me6TREN); dimethyl formamide (DMF); tetrahydrofuran (THF); phosphate buffered saline (PBS); poly(N-vinylcaprolactam) (PNVCL); sodium alginate (Na-Alg); N,N,N',N'-tetramethylethylenediamine (TEMED); ethylene oxide (EO). Abbreviations (light responsive hydrogels): N-isopropylacrylamide (NIPAAm); acrylic acid (AAc); ammonium persulfate (APS); azobenzene-branched polyacrylic acid (AzBPAAC); deoxycholate- β -cyclodextrin (D- β -CD); N,N'-methylenebisacrylamide (MBAAm); graphene oxide (GO); glycidyl methacrylate (GMA); dimethyl sulfoxide (DMSO); polypyrrole (PPy); 4-dimethylaminopyridine (DMAP). Abbreviations (electrical stimuli responsive hydrogels): Al(OH)₃; nanoparticles (AH NPs); acrylic acid (AAc); N,N'-dimethyl-acrylamide (DMAAm); N,N'-methylenebisacrylamide (MBAAm); graphene oxide (GO); acrylamide (AAm); sodium alginate (Na-Alg); potassium persulfate (KPS); N,N,N',N'-tetramethylethylenediamine (TEMED); micro-fluidic spinning (MFS); benzoin dimethyl ether (BDK); 2-acryloylamino-2-methyl-1-propanesulfonic acid (AMPS); PF127 diacrylate (PF127DA); dimethyl sulfoxide (DMSO); 2-hydroxy-2-methylpropiophenone (HMPP); 3-acrylamidophenylboronic acid (PBA); polydimethylsiloxane (PDMS); N,N-dimethylamino ethyl acrylate (DMAEA). Abbreviations (pH responsive hydrogels): poly(L-lactide)-co-poly(ethylene glycol)-co-poly(L-lactide) dimethacrylates (MA-PLLA-PEG-PLLA-MA); acrylic acid (AAc); N-isopropyl acrylamide (NIPAAm); 2-(dimethylamino)ethyl methacrylate (DMAEMA); N,N'-methylenebisacrylamide (MBAAm); N,N,N',N'-tetramethylethylenediamine (TEMED). Abbreviations (magnetically responsive hydrogels): N-isopropylacrylamide (NIPAAm); acrylamide (AAm); O-acetyl galactoglucomannan (AcGGM). Abbreviations (sound responsive hydrogels): polyethylene glycol (PEG); poly(ethylene glycol-*block*-poly(lactic-co-glycolic acid) (PEG-*b*-PLGA); phosphate buffered saline (PBS); N-hydroxy succinimide (NHS); poly(ethyleneimine) (PEI); poly(methacrylic acid) (PMAAc); poly(N-vinylpyrrolidone) (PNVP); 1-ethyl-3-(3-(dimethylamino) propyl)-carbodiimide hydrochloride (EDC); ethylenediaminetetraacetic acid sodium salt (EDTA); polyvinyl alcohol (PVA); N-isopropylacrylamide (NIPAAm); bovine serum albumin (BSA); N,N'-methylenebisacrylamide (MBAAm); ammonium persulfate (APS); N,N,N',N'-tetramethylethylenediamine (TEMED); cyclodextrin (CD); dimethylformamide (DMF); dimethyl sulfoxide (DMSO). Abbreviations (glucose responsive hydrogels): phenylboronic acid (PBA); polyethylene glycol (PEG); acrylamide (AAm); 2-hydroxyethyl methacrylate (HEMA).

Thus, hydrogels that possess important features including self-healing^{170,318} and extreme flexibility^{319–323} with superior mechanical properties^{324–326} and stretchability^{327,328} can be synthesized.

5.1. Hydrogels for superior mechanical applications

Hydrogels have immense applications in tissue engineering, wastewater treatment, wound healing, antimicrobial applications,³²⁹ and controlled drug release, but the lack of mechanical strength has limited their applications substantially.^{324,325} The bio-mimicking ability of hydrogels have made researchers explore the means of enhancing the mechanical properties of hydrogels. Since soft tissues such as tendons, ligaments, and other supporting tissues are tough materials, which are vulnerable to injury and incapable of regenerating spontaneously, materials with similar toughness and hydration properties could be a great choice for remodeling such injuries.³²⁶ To utilize hydrogels in mechanical strength demanding applications, increasing the toughness of hydrogels is a prerequisite. Many of the reported hydrogels are weak, brittle, and have low toughness, which somewhat limits their applications.^{330,331} Therefore, techniques of double networking,³³² interpenetrated networking,³²⁹ triple networking,³³³ synergistic copolymerization effects,³³⁴ and nano-additive enforced networking³²⁵ have been employed to tune the mechanical properties of hydrogels. For instance, Yan *et al.* developed double networked hydrogels of PAAm and gelatin reinforced with GO nanosheets (gelating/PAAm/GO) (Fig. 22a). Due to the hydrophilic nature of GO, it functions as a multi-crosslinker with PAAm and can interact with gelatin *via* electrostatic and/or hydrogen bonding interactions, which significantly increases its elasticity, fracture stress/strain, and softening properties relative to the neat PAAm and gelatin/PAAm hydrogels. The presence of GO made the hydrogel denser, resulting in the reduction of the swelling property. Additionally, the interactions between GO and gelatin caused the deterioration of self-recovery properties.³³² A semi-interpenetrating networked hydrogel of BC and CHT (Fig. 22b) was developed by Wahid *et al.* The CHT part of the hydrogel was cross-linked by glutaraldehyde, while the BC part adhered *via* hydrogen bonding. The resulted hydrogel demonstrated better mechanical and thermal properties than the neat hydrogels of BC and CHT. The scanning electron microscopic image exhibited a dense network structure, which could be due to the enhanced entanglement of bacterial cellulose in cross-linked chitosan networks.³²⁹ Triple-networked (Fig. 22c) hydrogels of PVA, PVP, and PAAc-Zn²⁺ obtained *via* similar physical-chemical crosslinking techniques were developed by Li *et al.* Formation of hydrogen bonding between PVA and PVP chains along with chemical-crosslinking of PAAc resulted in triple-networked hydrogels with superior tensile and frictional properties to those of neat PVA and PVP/PVA hydrogels.³³³ A combination of hydrophilic and hydrophobic polymeric segments can endow hydrogels with versatile properties. For example, hydrogel containing hydrophobic rich segments can provide hydrogel with stiffness and strength, whereas low hydrophilic segments can provide properties like stretchability and toughness. A mechanically enhanced copolymeric hydrogel fabricated from hydrophobic phenyl acrylate and hydrophilic AAm monomers was reported by Mredha *et al.* (Fig. 22c)



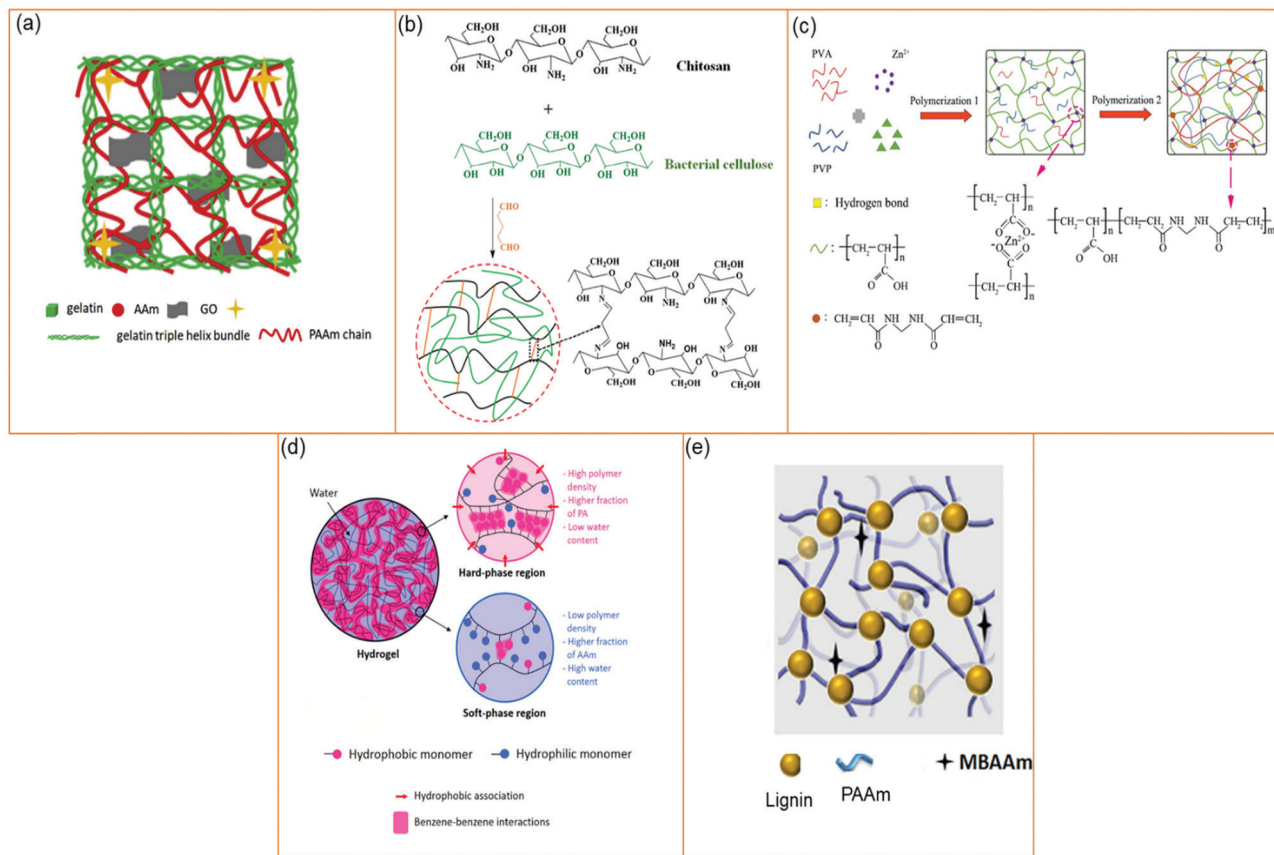


Fig. 22 Means of tuning the mechanical properties of hydrogels. (a) Double networking [reprinted with permission from ref. 332, ©Elsevier, 2018]. (b) Interpenetrated networking [reprinted with permission from ref. 329, ©Elsevier, 2019]. (c) Triple networking [reprinted with permission from ref. 333, ©Elsevier, 2019]. (d) Synergistic effect of copolymers [reprinted with permission from ref. 334, ©Elsevier, 2018]. (e) Nano-additive enforced networking [reprinted with permission from ref. 325, ©Elsevier, 2019].

Formation of lower water content and higher phenyl acrylate containing hard regions with high water content and higher AAm containing soft regions was observed.³³⁴ The presence of nanomaterials within hydrogel networks can significantly enhance the mechanical properties of hydrogels. The hydrogels reported by Chen *et al.* incorporated lignin nanoparticles within PAAm hydrogel networks. Presence of the lignin nanocomposite endowed the hydrogels with better compressive stress enabling them to distribute the applied load efficiently. The improvement was mainly due to the presence of nanonetworks and hydrogen bonding between the hydrogel forming materials.³²⁵

To use hydrogels in loadbearing areas, researchers have developed numerous methods, such as chemical cross-linking, hydrogel networking (*i.e.* interpenetrating and double networking), and nano-additives, to improve their mechanical properties.^{324–326} Table 3 summarizes the synthesis methods/techniques, hydrogel types, process flow, test results, and applications of several hydrogels with superior mechanical properties.

5.2. Hydrogels for antimicrobial applications

Tailoring high-performance and multi-functional properties of hydrogels, especially natural polymer hydrogels, has drawn attention recently.^{339,340} Different types of techniques like

double-network hydrogels,³⁴¹ nanocomposite hydrogels,³⁴² macromolecular microsphere composite hydrogels,³⁴³ polyampholyte hydrogels, *etc.*^{344,345} have been developed to impart functional properties. The produced hydrogels have the functional properties of high swelling in water, soft pliable nature, elastic properties, self-healing performance, and compatibility with human physiology. These improved properties have added a new dimension in the field of drug delivery, tissue engineering, food packaging products, cosmetics, and biomedical engineering.^{346–350} Many studies were performed to develop hydrogels as alternative materials for antibacterial applications. For example, the desired properties of hydrogels, such as hydrophilicity and porosity, can be integrated by selecting the types of monomers and crosslinkers. Moreover, some types of hydrogels also have inherent antibacterial properties. Based on the hydrogel matrices and antibacterial agents, antibacterial hydrogels are divided into (i) inorganic nanoparticle-containing hydrogels, (ii) antibacterial agent-containing hydrogels, and (iii) hydrogels with inherent antibacterial capabilities.^{351,352} However, antimicrobial hydrogels can be synthesized in the ways mentioned in Fig. 23.

Incorporation of metals is one of the most pristine and widely used techniques to functionalize antimicrobial properties, but with the recent development of nanoscience, the incorporation



Table 3 Preparation of hydrogels with superior mechanical properties

Synthesis method/techniques	Hydrogel type	Cross-linking method	Main materials	Applications	Ref.
Chemical cross-linking	Cellulosic nanomaterials (cellulose nanocrystals, bacterial cellulose fibers, and TEMPO-oxidized cellulose nanofibers) dispersed interpenetrating hydrogels	Ionic cross-linked networks	PAAm, polyelectrolyte Na-Alg	Wastewater treatment	324
Quinone	Nanofiber-reinforced gelatin	Chemical cross-linking	Deacetaldehyde chitin nano-fibrillated suspension, DI water, PTFE membrane	Agricultural and biomedical fields	326
Physical cross-linking	RSF based double networked hydrogels	RSF/SDS network	AAm, Irgacure 2959, SDS, NaCl, RSF, PTFE spacer	Strain sensors, touch screen pen, and the electronic skin of artificial robots	335
Physical cross-linking	The 3D-printed tough hydrogel of MAAc and NPAM	Hydrogen bonded cross-linking	DMSO, MAAc, NPAM, photo-initiator IRGACURE 2959	Soft robots, implant devices, and tissue engineering	336
Chemical-physical crosslinking	BC and CHT semi-interpenetrating networked hydrogels	Glutaraldehyde cross-linked network	BC membrane, CHT, glutaraldehyde	Antibacterial applications	329
Chemical-physical crosslinking	PAAm/lignin nanoparticle nanocomposite hydrogels	Free radical networking in lignin nanoparticle dispersion	PAAm, MBAAm, ascorbic acid, hydrogen peroxide	Tissue engineering or regeneration, artificial muscles, strong underwater antifouling materials	325
Chemical-physical crosslinking	Silicon dioxide/PVA composite hydrogels	Injection molding of the hydrolyzed solution	PVA, MTMS, HCl	Artificial articular cartilage, drug delivery, and biosensors	337
Chemical cross-linking	Hydrophobic and hydrophilic monomer-based hydrogels	MBAAm cross-linked network	Phenyl acrylate, AAm, DMSO medium, MBAAm, 2,2-azobisisobutyronitrile	Diverse load-bearing applications	334
Chemical-physical crosslinking	Triple-network hydrogels of PVP/PVA/PAAc	MBAAm cross-linked network	PVP, PVA, AAC, MBAAm, ZnCl ₂	Engineering applications with better mechanical properties and lower friction coefficients	333
Chemical cross-linking	Non-swellable gradient hydrogels	HCL cross-linked network	Sodium pyrophosphate dispersion, LAPONITE [®] , PAAm, HCL	Biomedical applications	338

Abbreviations: *N,N'*-methylene bis-acrylamide (MBAAm); sodium dodecyl sulfate (SDS); regenerated silk fibroin (RSF); methacrylic acid (MAAc); *N*-(pyridine-2-yl) acrylamide (NPAM); dimethyl sulfoxide (DMSO); bacterial cellulose (BC); methyltrimethoxysilane (MTMS); polyvinylpyrrolidone (PVP).

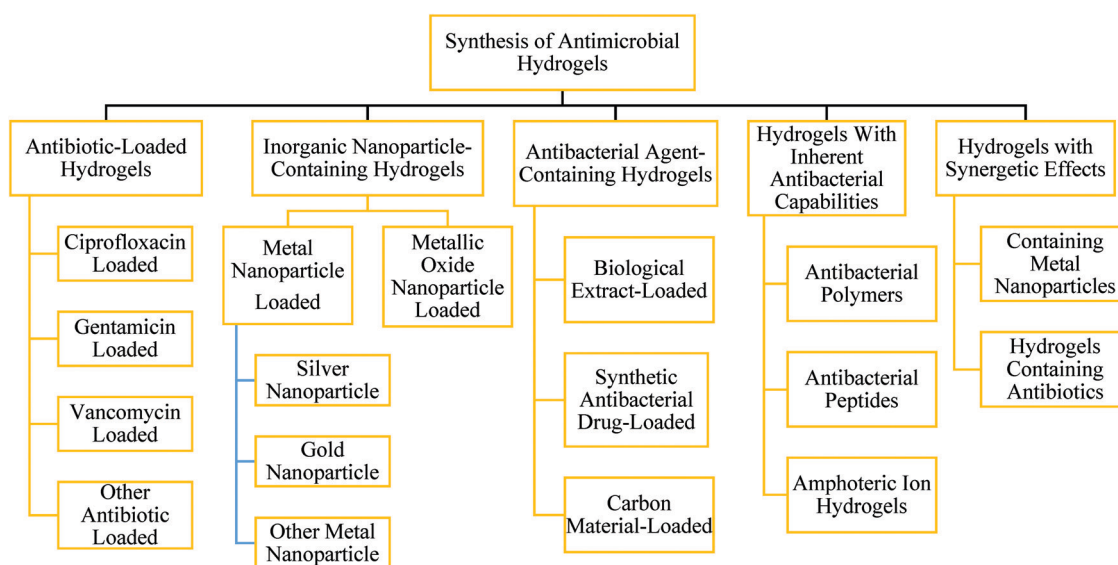


Fig. 23 Synthesis of antimicrobial hydrogels (based on ref. 351).

of metals, especially Ag, Au, Cu, and Zn, with hydrogels is done mainly in the form of NPs.^{351,353} Ag is most widely used due to its

good antibacterial properties and relatively low toxicity. However, other metals, such as gold, copper, and zinc, have their advantages



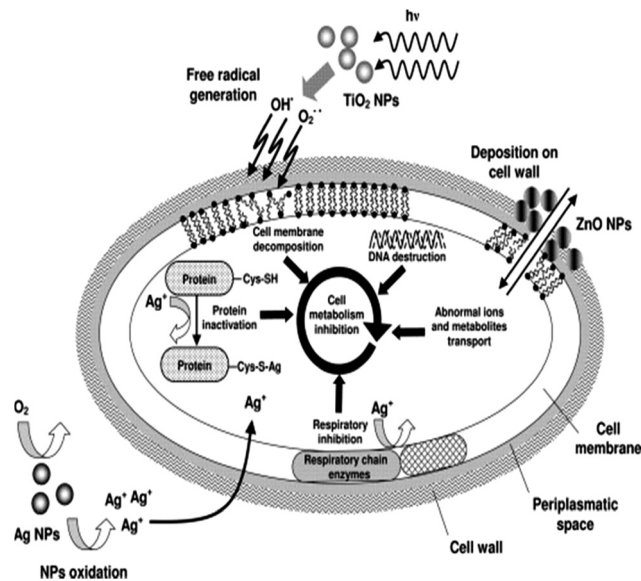


Fig. 24 Antibacterial mechanisms of metals and metal oxide NPs [reprinted with permission from ref. 354, ©Elsevier, 2013].

and provides antibacterial properties as well.³⁵² It is hypothesized that the interaction between silver ions (Ag^+) and the thiol group in proteins of the bacterial cell membrane is responsible for affecting the bacterial cell viability by inhibiting the replication of DNA (Fig. 24).³⁵¹

Both natural and synthetic polymers are used as the matrix of hydrogels containing Ag NPs. Polysaccharides, mainly alginate, chitin, CHT, and CMC, are common natural polymers.³⁵¹ The antimicrobial action of CHT is more rapid against fungi and algae than toward bacteria.^{354–356} The resistance against microbes depends on several intrinsic factors such as the type of CHT,³⁵⁷ the degree of CHT polymerization, the host, the natural nutrient constituency, the chemical or nutrient composition of the substrates or both, and the environmental conditions (e.g., substrate water activity, moisture or both).³⁵⁸

Both chitin and CHT have antimicrobial and metal-binding properties. Chitin- or CHT-based hydrogels such as the CHT/2-glycerophosphate/nano-silver hydrogel and silver molybdate nanoparticle/chitin matrix ($\text{Ag}_2\text{Mo}_2\text{O}_7$ /chitin) hydrogels are resistant to *E. coli*.^{359,360} The other polysaccharide hydrogels include the iota-carrageenan-based Ag NP hydrogel and the Ag NP-loaded PVA/gum acacia hydrogel; both actively show good antibacterial activity against the Gram-negative bacterium *E. coli*.^{361,362} The recent developments of antibacterial hydrogels incorporating metal particles and their oxides are summarized in Table 4.

5.3. Hydrogels for cell adhesive applications

The structure of hydrogels is analogous to that of biological soft tissues which have excellent potential to be used as scaffolds for cell growth and proliferation.^{380,381} A magnetic PAAm hydrogel synthesized by integrating magnetic nanoparticles into gelatin can act as a cell adhesive hydrogel interface. Furthermore, this gel can act as a multi-array cell culture matrix. The order, degree, and

distribution of cell adhesives, as well as cell–cell and cell–matrix interactions throughout the multilayer matrix, determine the cell behavior including emulating the extracellular matrix (ECM). It is possible to induce a different form of hepatocyte 3D spheroids and thus transition by controlling cell adhesion affecting the cell behavior. A magnetic anisotropic hydrogel structure can be formed using Fe_3O_4 MNPs, AAm monomers, MBAAm, and tetraethyl ethylenediamine all mixed in water. The solution is subjected to ultrasonic agitation in a polytetrafluoroethylene (PTFE) module. PAAm gelation is induced by heating (approx. at 50°C) after the exposure of the resulting solution to a magnetostatic field for a certain time. This hydrogel with a superior cell adhesive functionality is thought to hold great potential for anticancer drug and hypothermia therapy.^{382–385} A peptide modified PEG scaffold is a cell-adhesive hydrogel scaffold that can act as a vessel for human blood-driven endothelial progenitor cells (EPC). It is a potential cell source for applications like vascular tissue engineering. A mild photocrosslinking process is used to encapsulate the EPC within a PEG-based hydrogel. After cell culture and network formation to prepare EPC, a solution is formed by reacting the cell adhesive peptide ligand, arginyl glycol aspartic acid (RGDS), with acrylate–PEG–succinimidyl valerate (Acryl–PEG–SVA) to provide purified RGDS conjugated PEG (PEG–RGDS).¹⁸ A matrix metalloproteinase (MMP) sensitive peptide sequence (PQ) was also reacted with Acryl–PEG–SVA to give the Acryl–PEG–PQ–PEG–Acryl (PEG–PQ) conjugate. A solution of both PEG–PQ and PEG–RGDS was formed by dissolving both into PBS. Later, the hydrogel was formed by exposure to white light (Fig. 25a).^{386,387}

A polydopamine–polyacrylamide (PDA–PAAm) single network hydrogel with super-stretchability, high toughness, cell affinity, and tissue adhesiveness properties was synthesized. The PDA–PAAm hydrogel was prepared in the following two steps. In the first step, PDA was prepared by oxidizing dopamine (DA) under alkali conditions. In the second step, AAm was polymerized and crosslinked to form PDA–PAAm hydrogels (Fig. 25b).³⁸⁸

An alginate-based cell adhesive bio-hydrogel (AdhHG) is an important potential discovery in the field of biomedical engineering. Such hydrogels are capable of encapsulating and delivering mesenchymal stem cells (MSC) to the desired location and thus contribute to tissue engineering and regenerative medicine. Cell adhesion plays an important role in both cell regeneration and sealing tissue or coating implants in the desired location. L-DOPA amino acid (DA) modified alginate hydrogels show strong adhesion to cells. First, a methacrylate alginate hydrogel is synthesized by polymerization of the methacryloyl group in the alginate chain. DA hydrochloride is integrated to induce the crosslinking ability. The adhesive property is further improved by reacting with collagen emulating short peptides to form AdhHG. Crosslinking is carried out in the Ca^{2+} medium. Finally, the hydrogel is formed by photopolarization through exposure to blue-green light.^{389–392} Similarly, a novel peptide-based hydrogel containing cell adhesion and cell proliferation properties is expected to show inherent antibacterial characteristics and act as a potential scaffold for cutaneous wound healing. The hydrogel is synthesized from a series of peptides, Poly(Lys)_n(Ala)_m. These are derived from ring-opening polymerization of



Table 4 Information on hydrogels with different metal NPs

Metal	Synthesis technique	Hydrogel matrix	Bactericides	Applications	Ref.
Ag NPs	Electrochemical synthesis and rehydration	Alginate nanocomposite hydrogels	<i>S. aureus</i> , <i>E. coli</i>	Potential wound dressing	363
	Free radical polymerization and green process	Alginate/PVA silver nanocomposite hydrogel	<i>E. coli</i> , <i>S. aureus</i>	Wound dressing, water purification	364
	Free radical polymerization	NIPAAm-based nanogels	<i>E. coli</i> , <i>S. epidermidis</i>	Biomedical applications	365
	Cross-linking <i>via</i> radical redox polymerization	Sodium alginate-based semi-IPN hydrogels	<i>E. coli</i> , <i>S. aureus</i>	Drug delivery	366
	Synthesis at low temperature	Thermosensitive CHT/2-glycerophosphate/nanosilver hydrogels	<i>S. aureus</i> , <i>P. aeruginosa</i>	Wound dressing	359
	Free radical cross-linking polymerization and follow-up reduction of silver nitrate	P(MMA-co-MAA)/silver nanocomposite hydrogels	<i>S. aureus</i> , <i>B. subtilis</i>	Smart material	367
	Physical cross-linking in sodium tripolyphosphate as the cross-linker	CHT hydrogel beads	<i>E. coli</i> , <i>S. aureus</i>	Potential drug delivery carrier	368
	NaCMC was dissolved in distilled water. FA was added to the solution	FA cross-linked CMC hydrogel	<i>S. aureus</i> , <i>K. pneumoniae</i>	Cotton fabric	369
	<i>In situ</i> reduction of GO using vitamin C in the presence of heat (90 °C)	RGO-based composite hydrogel	N/A	Wastewater treatment	370
	Freeze-thaw method	QPVA hydrogel	<i>E. coli</i> , <i>S. aureus</i> , <i>P. aeruginosa</i> , MRSA, <i>E. coli</i>	Antimicrobial dressing	371
Au NPs	Incorporation of nanosized HAP particles into porous SF hydrogels	SF/nano-HAP hydrogel	<i>E. coli</i> , <i>S. aureus</i>	Bone tissue engineering	372
	Genipin cross-linking	Gelatin hydrogels	N/A	Carriers in drug delivery	373
	Au NPs through sodium borohydride reduction method and liposomes through the standard extrusion method	AuC-liposome hydrogel	<i>S. aureus</i>	Microbial infections	374
ZnO	The hydrogel was made from ZnO NWs and the combination of CHT and AAc. ZnO NWs were prepared by a hydrothermal strategy using zinc acetate with NaOH as precursors and PEG as an assistant. CHT-co-AAc hydrogels were prepared by free-radical graft polymerization	CHT-based composite hydrogel	<i>E. coli</i> , <i>S. aureus</i>	Biomaterials, cosmetics, food packaging	354
	CHT pellet was mixed with alginate solution as a cross-linker to strengthen the hydrogel through a freeze-dry process	Alginate hydrogel	<i>E. coli</i> , <i>S. aureus</i> , <i>C. albicans</i> , MRSA	Wound infections	375
	ZnO-PEGMA and AG-N3 IPN nanocomposite hydrogels were synthesized under UV irradiation	AG with IPN structure	Gram-positive and Gram-negative bacteria	Wound dressing	376
CMCh solution cross-linked with epichlorohydrin at 80 °C	CMCh hydrogel	Gram-positive and Gram-negative bactericides	Applications in biomedical fields	377	
Ni NPs	Nickel NPs prepared by a hydrothermal method	Ni NP chitin nanogels	<i>S. aureus</i>	Biomedical field	378
MgO	κC was blended with Na-CMC dissolved in distilled water	Modified κC hydrogel	N/A	Drug delivery, especially in gastrointestinal tract studies	379

Abbreviations: FA, fumaric acid; GA, gum acacia; HEMA-2, hydroxyethyl methacrylate; IPN, interpenetrating polymer network; MRSA, methicillin-resistant *S. aureus*; PBS, phosphate buffered saline; PMAAc, poly(methacrylic acid); QPVA, quaternized polyvinyl alcohol; RGO, reduced graphene oxide; NW, nanowires; AAc, acrylic acid; SF, silk fibroin; CMCh, carboxymethyl chitosan; κC, κ-carrageenan; PEGMA, poly(ethylene glycol) methyl ether methacrylate; Ni NPs, nickel nanoparticles; AG-N3, 4-azidobenzoic agarose; NaCMC, CMC sodium salt; HAP, hydroxyapatite.

N-carboxylic anhydride (NCA), *i.e.* NCA-Lys and NCA-Ala monomers. PEG-amide succinimidyl glutarate (ASG) is chemically cross-linked with peptides to form a hydrogel exhibiting cell adhesion properties. Wound dressings containing such hydrogels provide not only resistance against infections but also a suitable physiological environment for cell generation.^{393–396}

Another general cell adhesive hydrogel synthesis process starts with prepolymer solutions and several cross-linking methods including chemical, enzymatic, or photoreactions (Fig. 26A). For a successful tissue engineering process, an additional method is also required including tailoring biomechanical properties, tailoring degradability, tailoring bioactivity, and finally cell culture. Biomechanical properties can be improved by increasing the polymer concentration and by changing the architecture like linear,

branched, *etc.* (Fig. 26B). The degradation properties of hydrogels can be controlled by the integration of crosslinkers in polymer networks. For instance, the incorporation of a matrix metalloproteinase sensitive peptide sequence in hydrogels makes them prone to cell-mediated degradation (Fig. 26C). The bioactivity, another important property for cell adhesion and proliferation, of hydrogels can be improved by binding bioactive compounds with hydrogels (Fig. 26D).³⁹⁷ For example, a collagen-binding peptide is incorporated in an alginate hydrogel.³⁹⁸

5.4. Hydrogels for self-healing applications

Self-healing is the capability of materials to recover from their damage themselves. Self-healing materials are considered as the next-generation materials for high-performance structures.



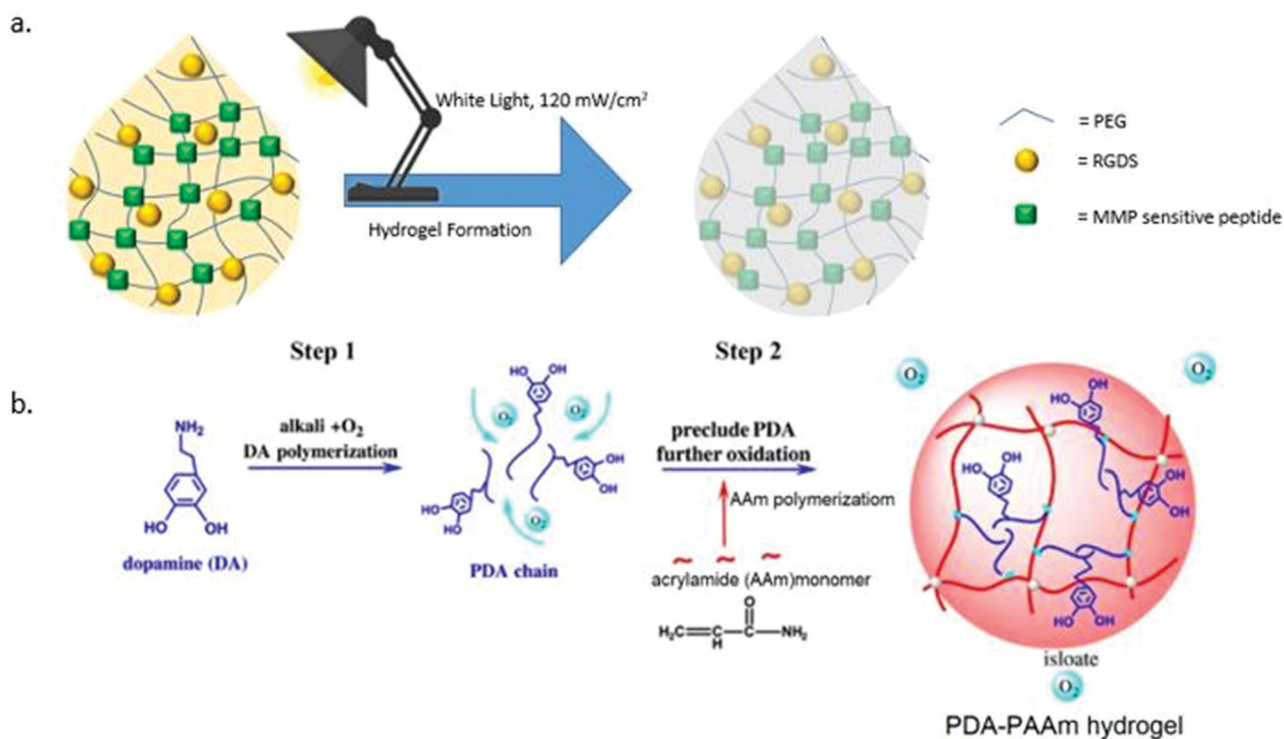


Fig. 25 (a) Schematic diagram of hydrogel synthesis from the PEG–RGDS and PEG–PQ solution [reprinted with permission from ref. 386, ©Springer Nature, 2015]. (b) Synthesis of PDA–PAAm hydrogels [reprinted with permission from ref. 388, ©Springer Nature, 2017].

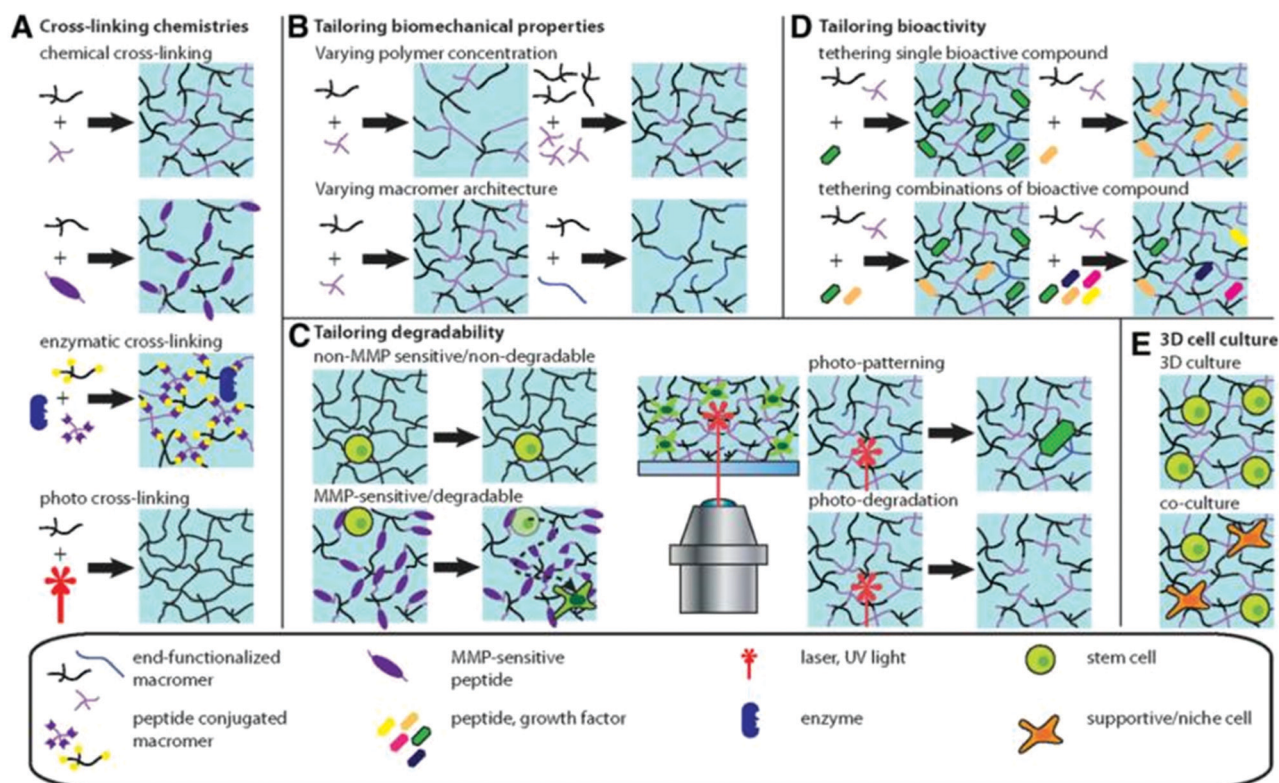


Fig. 26 Schematic representation of the synthetic hydrogel for cell adhesion and proliferation. (A) Cross-linking chemistries. (B) Tailoring biomechanical properties. (C) Tailoring degradability. (D) Tailoring bioactivity. (E) 3D cell culture [reprinted with permission from ref. 398, ©AlphaMed Press, 2015].



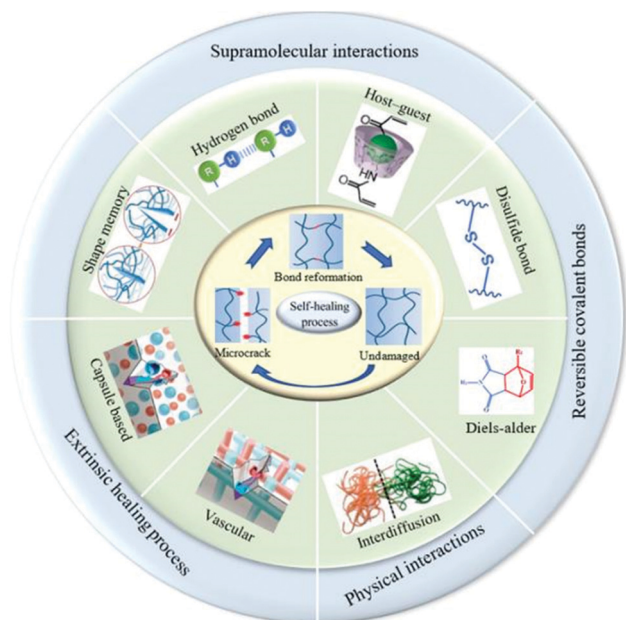


Fig. 27 Chemistry of the synthesis of self-healing hydrogels.⁴⁰⁰

This fascinating property can also be induced in hydrogels. Several underlying mechanisms of self-healing hydrogels are mainly divided into two broad categories: dynamic covalent bonds and non-covalent interactions (Fig. 27). Self-healing hydrogels possess dynamic covalent bonds that are mostly synthesized from Diels–Alder reaction, coordination bonds, imine bonds, boronate ester bonds, and disulfide bonds, whereas noncovalent interaction methods include hydrogen bonds, host–guest interactions, hydrophobic interactions, and electrostatic interactions.³⁹⁹

The chemistry of self-healing can be successfully incorporated in both natural and synthetic polymers (Fig. 28). The generally

used natural polymers to synthesize self-healing hydrogels are polysaccharide-based polymers including alginate, chitosan, and hyaluronic acid. Self-healing hydrogels with natural polymers are normally biocompatible. Synthetic polymers including PEG, PAAc, PVA, and PAAM give stronger and more elastic self-healing hydrogels.⁴⁰¹

A multifunctional composite self-healing hydrogel can be developed from a series of Li–alginate/poly(acrylamide-*co*-stearyl methacrylate) [Li–alginate/P(AAm-*co*-SMA)] hydrogels with a fully physically cross-linked interpenetrating network.⁴⁰² In addition to their excellent stretchability and self-healing ability, the produced hydrogels exhibit the maximum fracture energy that enables them to be used as fire-resistant materials.⁴⁰³ A rapid self-healing hydrogel was developed by aligning the polymer network with dangling hydrocarbon side chains containing polar functional groups. These groups can be hydrophilic and hydrophobic moieties that allow the side chains to mediate hydrogen bonding across two separate hydrogel pieces or a rupture in the hydrogel. A polysaccharide derivative cross-linked with PVA forms a hydrogel that is capable of displaying rapid self-healing behavior when subjected to rupture. The hydrogel synthesis technique involves the extraction of bioactive laminarins (polysaccharides) from alginic acid, fucoidan, or some other seaweeds. These laminarins contain β -glucan which is modified by reacting with phenylboronic acid. Later, the resultant biopolymer and PVA are cross-linked by boronate esterification and form a self-healing hydrogel.^{404,405}

Another type of self-healing hydrogel called a fluorochromic hydrogel that responds to light and ferric (Fe^{3+}) ions shows decent self-healing capability. Such a hydrogel is synthesized *via* the physical crosslinking of PVA. γ -Cyclodextrin-spiropyran (γ -CD-SP), a fluorophore, forms hydrogen bonds with PVA and thus is integrated into the PVA gel. The presence of tannic acid creates numerous binding sites to the PVA chain. This helps to

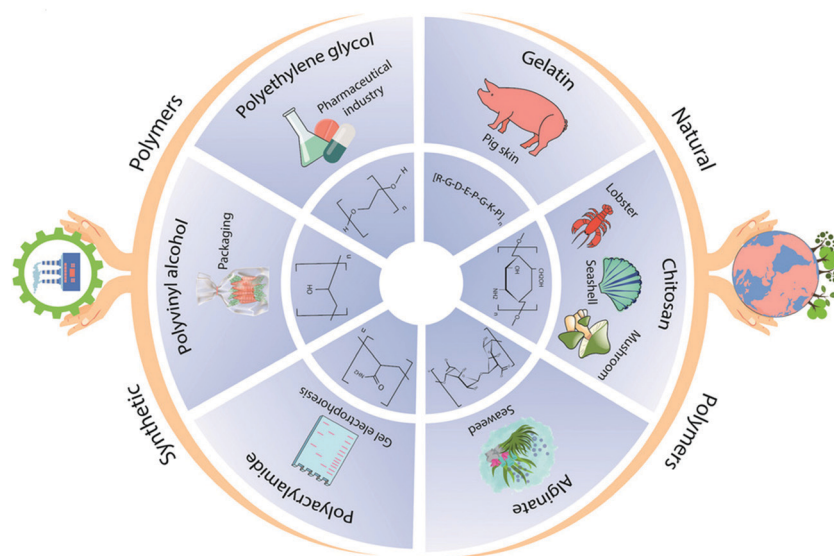


Fig. 28 Synthetic and natural polymers used to synthesize self-healable hydrogels are highlighted here [reprinted with permission from ref. 401, ©John Wiley and Sons, 2019].



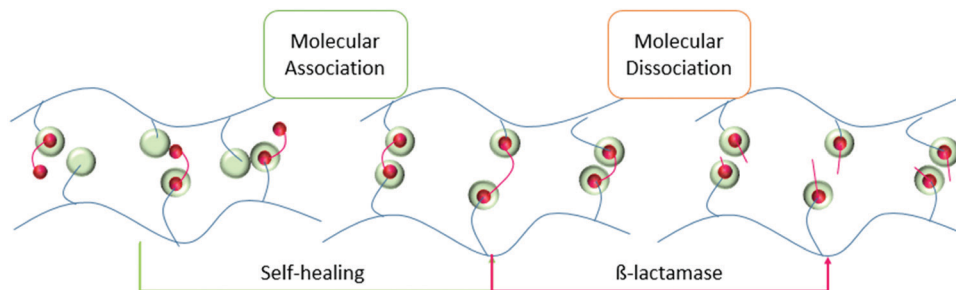


Fig. 29 Schematic diagram of molecular association and dissociation [reprinted with permission from ref. 409, ©American Chemical Society, 2020].

Table 5 Preparation of hydrogels for special applications

Special properties	Synthesis method/ techniques	Hydrogel type	Materials	Applications	Ref.
Heavy metal adsorption	Physical crosslinking	Cellulose-based	Cellulose, glycine, NaOH, acetic acid	Wastewater treatment & cartilage tissue engineering in soft electronics	411
Biocompatibility, Fe ³⁺ removal	Ionotropic crosslinking	Cellulose-CHT based	CHT, AA, alkali lignin, NH ₄ OH	Tissue engineering, wound healing, regenerative medicine, & water treatment	412
Super-absorbency	Chemical crosslinking	Lignin based	Lignin, montmorillonite, K ₂ S ₂ O ₈ -Na ₂ SO ₃ , AAc and MBAAm	Cu(II) ion removal	416
Higher compressive and tensile strength	Physical crosslinking/ <i>in situ</i> free radical polymerization	PAAm/lignin NPs based	AAM, lignin dispersion, MBAAm, ascorbic acid, and hydrogen peroxide water solution	Tissue engineering	325
Super-absorbency to gatifloxacin	Chemical crosslinking/chemical co-polymerization	Alginate based	PDA particles, alginate hydrogel (Alg-PDA), ammonia aqueous solution of sodium periodate and CaCl ₂	Drug delivery	414
High mechanical toughness with shape memory	Chemical crosslinking	Composite based	PF127, DA, PLGA and GO	Biomedical applications as drug carriers and antibacterial scaffolds	413
Viscoelastic solid-like properties	Chemical crosslinking	Composite based	DNA, synthetic hectorite (SWN), alkaline cations	Structural applications, such as gas barrier films and load-bearing applications	417
Viscoelastic	Chemical crosslinking	Composite based	PVA and PVP polymer mixture, brine, resorcinol solution, formaldehyde, NaOH	Water shut-off performance at higher temperatures	418
Superabsorbent	Cross-linked/free radical co-polymerization	CMTKG based	CMTKG, Na-Alg, K ₂ S ₂ O ₈ , MBAAm	Water conserver, soil conditioner and nutrient carrier	419
3-D printing performance	Physical cross-linking	Nanocomposite based	LREH aqueous dispersion, aqueous solutions of Na-Alg and PAAS ^{420,421}	Electronic skin, wearable electronics, and soft robotics	415

Abbreviations: chitosan (CHT), acetic acid (AA), acrylic acid (AAc), *N,N'*-methylenebisacrylamide (MBAAm), polydopamine (PDA), Pluronic F127 diacrylate (PF127 DA), poly(lactide-*co*-glycolide) (PLGA); graphene oxide (GO); polyvinylpyrrolidone (PVP), polyvinyl alcohol (PVA), sodium alginate (Na-Alg); layered rare-earth hydroxide (LREH); sodium polyacrylate (PAAS); alginate hydrogel (Alg), carboxymethyl tamarind kernel gum (CMTKG).

improve both the mechanical strength and self-healing ability of the hydrogel (Fig. 29).^{406–408}

Similarly, a self-healing hydrogel based on CNC can be synthesized *via* a one-pot polymerization technique. Herein, sodium alginate along with CNC acts as a macro-cross-linker. The reaction is initiated by introducing the aldehyde group *via* mild oxidation of both CNC and sodium alginate. Next, a Schiff-base linkage is incorporated to bind the CNC surface with the oxidized sodium alginate core. The hydrogel is capable of self-healing within several hours of dissociation at room temperature.^{400,410}

5.5. Other applications

Hydrogels are emerging materials that have attracted significant fundamental and applied interest for wastewater treatment,⁴¹¹ tissue engineering,^{325,412} drug delivery,^{413,414} wearable electronics,⁴¹⁵ and

energy-storage materials.³¹⁴ Apart from the aforementioned synthetic processes, the following recent works of functional hydrogels have extended their applications in numerous fields (Table 5).

6. Future prospects and conclusion

Hydrogels, a unique class of soft materials, have significant potential to be used in a wide range of applications including biomedicine, skin, and personal care products. Due to their significant potential, over the past few decades, rapid integration of 3D structures and easy customization with advanced synthesis techniques have spurred the popularity of hydrogels with a wide variety of applications, thus attracting research attention. To cope with these exponential demands, researchers are continuously developing new design and synthesis strategies. In this paper,



some recently developed hydrogels and their fabrication techniques have been summarized. Researchers are developing several processes to synthesize stimuli-responsive and functional hydrogels. However, numerous complexities associated with hydrogels mimicking the natural 3D structure have been reported. Multi-stimuli (physical, chemical, and biological)-responsive hydrogels mimicking the natural 3D structure and improvements in their responsive characteristics could be developed in future research. Additionally, these 3D structured hydrogel fabrication techniques inevitably destroyed the intrinsic hydrophilicity and biocompatibility of a hydrogel. These research booms involve the fabrication of diverse hydrogels in combination with different polymers, which also directs to the explanations of new mechanisms of the external stimuli-responsive hydrogel. The scope for developing smart hydrogels with desired functional and intact intrinsic physicochemical properties is yet to be explored.

In particular, substantial research is required to develop novel smart hydrogels with complex but programmed self-folding, twisting, and bending behaviors. An adverse immune response occurs when hydrogen scaffolds are inserted into a body which may lead to the rejection of scaffolds. Thus, future research should focus on synthesizing such hydrogels that can control and reduce immune cells like macrophages and adjust the plasticity and reprogramming to form/repair/reconstruct tissues. Another important property of natural hydrogels is having less toxicity. However, during the manufacturing process, different solvents have been used which may increase the toxicity level. Future research should focus more on incorporating natural materials in cross-linked hydrogels. Future research should also emphasize on scaling the size of hydrogels down to the single-cell sampling level. This is important as the present sequencing in bulk samples provides information on the population level, losing key information about biological subsets within the sample. It is possible to individualize sequencing 'omic' data on a cell-by-cell level by partitioning single cells into separate wells or droplets.

Injectable hydrogels have recently attracted the significant attention of researchers as they offer several benefits including cytocompatibility, non-invasive administration, tunable mechanical properties, high permeability, controllable degradability, and injectability, and these hydrogels can be used as scaffolds or as carriers of therapeutic agents such as drugs, cells, and proteins. However, several essential challenges still need to be overcome to use these injectable hydrogels successfully. Two important properties for the effective application of injectable hydrogels are strength and degradation. Although researchers are now producing high-strength hydrogels, the balance of strength with degradation is crucial for hydrogels. The degradation rate of hydrogels should be well adjusted with cell adhesion and proliferation. Also, developing advanced controllable electro-sensitive hydrogels with a faster response rate for smart drug delivery is another area to explore further in depth.

Finally, we may conclude that significant developments have been made over the past few decades to improve the properties of hydrogels and these improvements need to be continued in the near future to improve, modify, and create a new paradigm

of application opportunities. Therefore, the authors of the manuscript feel that a comprehensive overview of synthesis processes and understanding the strategies of tuning special functional properties of smart hydrogels are a pressing need.

Conflicts of interest

The authors have no potential conflicts of interest.

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