

Research progress on the preparation, characterization, and applications of hydrogels

Zixi Wang

Guangzhou Dublin International College of Life Sciences and Technology, South China Agricultural University, Guangzhou, China

3090505246@qq.com

Abstract. Hydrogels are functional polymeric materials with a three-dimensional network hydrophilic structure. Benefiting from excellent biocompatibility, high water retention, and tunable physicochemical properties, they have become a research hotspot in food, biomedicine, and other fields. This paper systematically reviews the preparation techniques, characterization systems, and diverse applications of natural polymer-based hydrogels. It combs through the principles, advantages, and application limitations of five mainstream preparation methods—thermal induction, physical crosslinking, chemical crosslinking, ionic crosslinking, and enzymatic crosslinking—and clarifies the regulatory mechanisms by which different crosslinking modes affect the microstructure and macroscopic properties of hydrogels. Meanwhile, from the three dimensions of structure, properties, and function, this paper comprehensively presents core characterization techniques such as SEM, FT-IR, XRD, and rheological testing, and elucidates the intrinsic correlations among the microstructure, physicochemical properties, and practical functions of hydrogels. On this basis, it summarizes the core application scenarios and technical advantages of hydrogels in food texture modification, bioactive substance delivery, smart packaging, food 3D printing, and biomedicine.

Keywords: hydrogels, preparation, characterization, applications

1. Introduction

Hydrogels are hydrophilic materials with a three-dimensional network structure, constructed from hydrophilic polymers through physical crosslinking, chemical crosslinking, or enzymatic crosslinking [1]. Owing to their unique network topology, hydrogels can absorb and lock in large amounts of water while maintaining their structural integrity. With good biocompatibility, high water retention, tunable mechanical properties, and degradability, hydrogels show great application potential in biomedicine, tissue engineering, environmental remediation, and food science [2]. The basic raw materials for hydrogels are widely derived from natural macromolecules (such as proteins and polysaccharides) and synthetic polymers. Among them, natural polymers such as Soy Protein Isolate (SPI), Whey Protein Isolate (WPI), sodium Alginate (ALG), Pectin (PEC), and starch are favored for being safe, non-toxic, and abundant. The basic preparation methods include heat treatment, ionic crosslinking, enzymatic crosslinking, physical modification (e.g., ultrasonication, high-pressure treatment), and composite crosslinking combining physical with chemical/enzymatic methods [3]. By

regulating the material composition and crosslinking strategy, hydrogel systems with specific physicochemical properties can be precisely designed and constructed.

At present, hydrogel preparation techniques have evolved from single-component crosslinking to the stage of multi-component synergistic composite network construction. In specific preparation cases, physically crosslinked hydrogels built using physical interactions (such as electrostatic interactions, hydrogen bonds, and hydrophobic interactions) exhibit good self-healing and mild preparation conditions; chemical crosslinking, by contrast, endows the system with higher mechanical strength and chemical stability through covalent bonds [4]. For example, in the preparation of sodium alginate-acetate starch composite hydrogel beads, the ionic dropping method is often used: sodium alginate and acetate starch are mixed in aqueous solution at 70 °C, the target active substance is added after cooling, and the mixture is dropped through a needle into a calcium chloride solution, where rapid solidification is achieved by ion bridging between calcium ions and the carboxyl groups of sodium alginate [5]. For starch-based composite hydrogels, a thermal gelatinization blending method can be used, in which potato/cassava starch is gelatinized in a water bath at 90 °C and then mixed with chitosan or sodium alginate and cooled to form the gel [6]. In addition, a two-step dual-enzyme sequential crosslinking method (e.g., catalyzed by transglutaminase, TGase) and a composite dropping-solidification technique that mixes polyphenols with natural proteins (such as SPI, WPI, BSA), sodium alginate, and pectin also significantly improve the density and encapsulation rate of the hydrogel network structure [7].

Hydrogel characterization techniques are the core means to reveal the 'structure-property-function' relationship of hydrogels, and are usually divided into three dimensions: structural, property, and functional characterization. Structural characterization aims to clarify the micro-topology and molecular conformation of hydrogels [4], such as observing the network pore-size distribution by Scanning Electron Microscopy (SEM) [8], and analyzing intermolecular chemical bonds and crystalline states by Fourier-Transform Infrared Spectroscopy (FT-IR) and X-Ray Diffraction (XRD) [9]. Property characterization focuses on the intrinsic physicochemical attributes of hydrogels, including evaluating their viscoelasticity and swelling/deswelling rates with a rheometer, and measuring texture properties (e.g., hardness, springiness, and cohesiveness), freeze-thaw stability, and thermogravimetric analysis (TGA). Functional characterization simulates actual application scenarios to evaluate the behavioral performance of hydrogels under specific environments, such as the release kinetics of active components, antioxidant activity retention, and antibacterial interception efficiency in a simulated *in vitro* gastrointestinal digestion environment [3]. For example, in a bigel system composed of alginate and monoglyceride oleogel, characterization of texture and rheological properties confirmed that reducing the oleogel content can effectively improve the hardness and thermal stability of the system, providing a quantitative basis for the mechanical regulation of complex multiphase food systems [10].

In the food industry, hydrogels show broad application prospects owing to their multifunctional properties, mainly in four scenarios: texture modification, bioactive substance delivery, smart/active packaging, and food 3D printing. First, as food texture modifiers, hydrogels of plant proteins (such as soybean and pea proteins) can accurately simulate the texture and juiciness of real muscle fibers, playing a key texture-supporting role in plant-based alternative foods such as artificial meat [11]. Second, as intelligent delivery carriers for bioactive components, the three-dimensional network structure of hydrogels can effectively encapsulate hydrophobic polyphenols (such as quercetin, resveratrol, and curcumin) and functional factors that are sensitive to heat, light, and acid, resist erosion by gastric acid, and achieve responsive release in the intestine, thereby greatly improving their oral bioavailability [12]. Third, in active food packaging, polysaccharide-protein composite hydrogels have uniform and dense pores and a large specific surface area, can rapidly absorb environmental moisture and slowly release natural antimicrobial agents, and can significantly extend food shelf life and

reduce microbial contamination risk [13]. Moreover, in biomedicine, hydrogels also have great application value; owing to their excellent bionic performance, highly tunable water absorption, biocompatibility, and high degradability, hydrogels are widely used in tissue engineering, flexible sensors, and drug delivery systems, playing a significant role in promoting tissue regeneration and wound healing and in improving drug targeting ability and utilization [2]. Finally, in food 3D printing, reinforced-crosslinked hydrogels, as 'bio-inks', overcome the poor printability of natural polymers and greatly improve the precision and shear-thinning stability of printed products [13].

In summary, hydrogel preparation methods have formed a large system covering physical, chemical, and biological enzymatic approaches, their characterization means are increasingly complete, and they play an irreplaceable role in the diverse applications in the food field. However, current preparation techniques still face certain limitations: physically crosslinked gels have high environmental sensitivity and insufficient mechanical strength, while chemical crosslinking may introduce potential safety toxicity and has relatively high synthesis costs. Looking ahead, the development trend of hydrogels will focus on the following directions: first, the development of efficient physical/enzymatic composite crosslinking technologies based on fully natural, 'clean label' materials; second, the in-depth development of intelligent hydrogels with multiple stimulus responsiveness (such as dual pH, temperature, and enzyme responses) to achieve precise targeted delivery and dynamic packaging warning [2]; third, the promotion of the industrial application of green hydrogel bio-inks with high printing precision and low energy consumption in customized nutritious food 3D printing.

2. Preparation of hydrogels

2.1. Thermal induction method

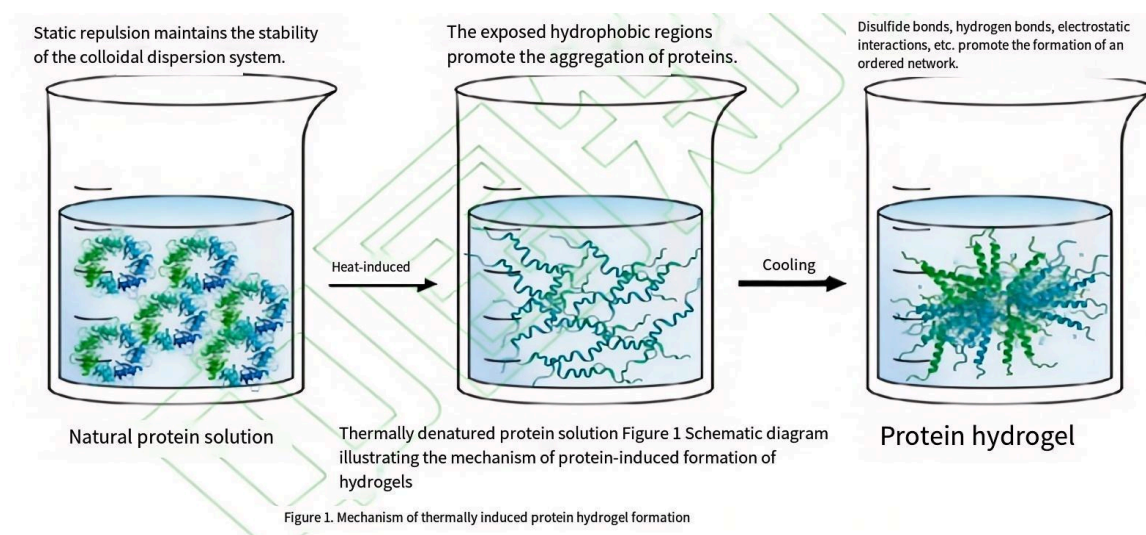


Figure 1. Schematic of hydrogel preparation by thermal induction method [11]

Thermal induction refers to a method of preparing composite hydrogels by regulating the crosslinking degree of polysaccharides and proteins through heat treatment [1]. As shown in Figure 1, during heating, polysaccharides (such as starch) and proteins undergo gelatinization and denaturation, respectively, promoting the full exposure of active sites such as hydrophobic groups and sulfhydryl groups inside the molecules; then, during cooling, macromolecules crosslink through the synergistic effect of hydrogen bonds, hydrophobic

interactions, electrostatic interactions, and disulfide bonds, driving molecular rearrangement and finally constructing a stable three-dimensional network structure [11]. Heating temperature is the core control factor of this preparation process; by regulating the secondary structure of proteins (e.g., reducing alpha-helix content and increasing beta-sheet content), it directly determines the intermolecular interaction strength and thus significantly affects the uniformity of gel network pores, mechanical properties, and thermal stability.

2.2. Physical crosslinking method

Physical crosslinking mainly relies on reversible non-covalent interactions to construct the three-dimensional polymer network of hydrogels, without introducing chemical crosslinking agents. In the specific preparation process, polyphenol molecules (such as tannic acid, gallic acid, or epigallocatechin gallate) are first dissolved with natural or synthetic polymer matrices (such as sodium alginate, soybean protein nanofibers, polyvinylpyrrolidone, or polyvinyl alcohol) in an aqueous medium to formulate a uniform precursor mixed solution containing charged groups, phenolic hydroxyl groups, and hydrophobic regions. Then, the physicochemical environment of the system is regulated to induce non-covalent interactions. Among them, as shown in Figure 2, electrostatic attraction between charged polymer chains or induced by cations can drive the self-assembly of molecular chains [14]; the abundant phenolic hydroxyl groups in polyphenol molecules combine with the polymer matrix to form a dense dynamic reversible hydrogen-bond network, which, as an energy dissipation site, not only constructs the three-dimensional skeleton of the gel but also endows the material with excellent mechanical toughness and self-healing properties; at the same time, the hydrophobic regions of molecular chains and polyphenol structures spontaneously aggregate in the aqueous phase to form hydrophobic crosslinking points; for specific systems containing polyvinyl alcohol, a cyclic freeze-thaw process can also be combined to induce polymer chain crystallization and form physically microcrystalline crosslinking regions [4]. Finally, the system rapidly completes self-assembly and gelation at room temperature or under mild physical conditions; the gelation time of some supramolecular systems can be as short as 15 seconds, thereby successfully obtaining physically crosslinked hydrogels with high water content, tunable mechanical properties, and good biocompatibility.

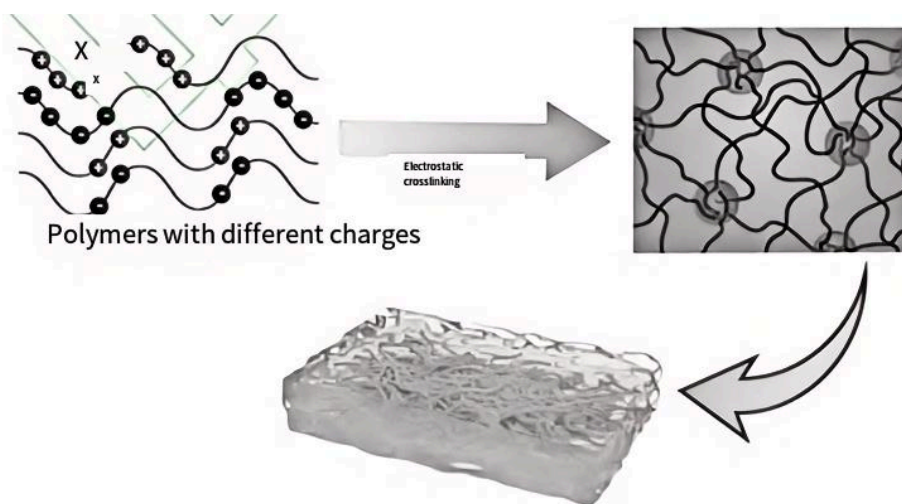


Figure 2. Schematic of hydrogel preparation by physical crosslinking method [4]

2.3. Chemical crosslinking method

Chemical crosslinking mainly uses covalent bonds to construct a structurally stable three-dimensional polymer network, usually requiring the introduction of a catalytic system such as an initiator, crosslinking agent, or specific enzyme [4]. In the specific preparation process, precursor monomers or polymer derivatives containing specific active functional groups (such as acrylic acid, polyphenol-modified hyaluronic acid) are first dissolved in an aqueous phase to formulate a uniform precursor reaction system [15]. Then, covalent crosslinking is induced according to the adopted chemical reaction mechanism: as shown in Figure 3, one is free-radical polymerization, in which, under the action of a crosslinking agent and an initiator, free radicals between low-molecular-weight monomers or molecular chains polymerize and crosslink to form a covalent network structure [16];

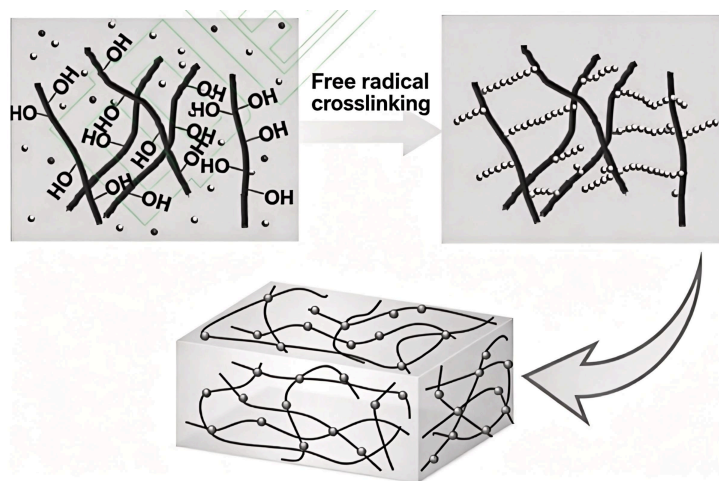
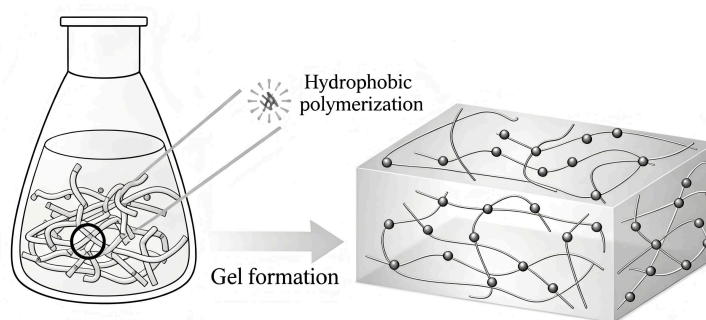


Figure 3. Schematic of free-radical polymerization [16]



Sabirication schematic of hydrophobically aggregated crosslinked hydrogels

Figure 4. Schematic of enzymatic crosslinking polymerization [4]

As shown in Figure 4, the other is enzymatic crosslinking, in which a specifically recognizing enzyme (such as tyrosinase) is added to the system, and the enzyme's high affinity for specific polyphenol structures (such as catechol/pyrogallol groups) efficiently catalyzes the oxidative coupling of intra- or inter-chain functional groups of polymer chains; this process has high reaction selectivity and extremely fast gelation speed (the gel time of some systems can be shortened to a few seconds) [17]. In addition, the chemical activity

of polyphenols can be combined to construct dynamic covalent bonds (such as borate ester bonds and Schiff base bonds), endowing the gel's chemical skeleton with environmental responsiveness. Finally, precursor molecules are irreversibly or dynamically crosslinked through covalent chemical reactions to form a chemically crosslinked hydrogel with high mechanical strength, structural stability, and specific intelligent response characteristics.

2.4. Ionic crosslinking method

Ionic crosslinking relies on the coordination of metal ions or charged polysaccharides with anionic groups such as protein carboxyls to form ionic bridges and build a three-dimensional gel network. Divalent calcium ions can form a network crosslinking structure, while monovalent sodium and potassium ions only assist in regulating gelation through charge shielding [3]. As shown in the Figure 5, the monomer solution is first polymerized to form a primary chemically crosslinked hydrogel, which is then immersed in a solution of iron ions and sulfate ions; the metal ions form ionic coordination/ionic interactions with carboxyl and amino groups on the polymer chains to construct ionic crosslinking points, yielding an ionically crosslinked double-network hydrogel [18]. The pH and ion concentration of the system directly determine the crosslinking efficiency; near the isoelectric point of proteins, the molecular electrostatic repulsion is weakest and a denser network is more easily formed—for example, adjusting the soy protein isolate-chitosan system near the isoelectric point can significantly improve the gel's water-holding capacity and rheological properties [19]. This method has mild reaction conditions and controllable gelation speed, and can avoid the drawback of high-temperature heat treatment destroying heat-sensitive active substances; it is suitable for the embedding of probiotics and functional nutrients and the preparation of cultured-meat cell scaffolds. However, the stability of the gel network is easily disturbed by environmental ionic strength, and its mechanical strength is limited when used alone; it is often combined with enzymatic crosslinking to build a double network for enhanced performance. At present, this process is mostly used for the steady-state delivery of food active substances, and future research focuses on the development of pH/ion dual-responsive intelligent protein hydrogel carriers.

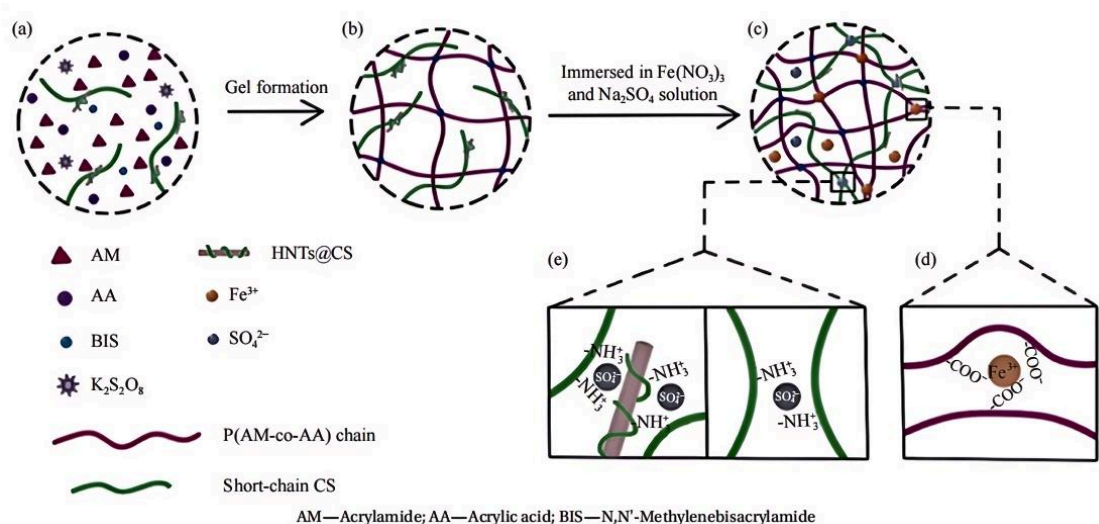


Figure 5. Schematic of hydrogel preparation by ionic crosslinking [18]

2.5. Enzymatic crosslinking method

Enzymatic crosslinking relies on biological enzymes to catalyze the formation of stable covalent isopeptide bonds between protein molecules. With mild reaction and excellent biocompatibility, it is a green preparation method for food-grade hydrogels. The core commonly used enzyme is transglutaminase (TGase), which catalyzes the formation of crosslinks between glutamine and lysine residues to build an ordered porous network [3]. As shown in the Figure 6, gelatin microspheres are enzymatically crosslinked by microbial Transglutaminase (mTG) to form a macroporous injectable hydrogel. mTG catalyzes the formation of isopeptide bonds between glutamine (Glu) and lysine (Lys) residues on gelatin chains, realizing covalent enzymatic crosslinking within microgels and between microgel particles, yielding a porous bulk hydrogel suitable for cell delivery and tissue engineering [20]. Compared with heat treatment, the soybean protein microgel prepared by TGase has larger particle size, more regular structure, and significantly improved foam stability [1]; tyrosinase and peroxidase can oxidize phenolic groups to assist crosslinking, enriching the gel regulation pathway [21]. In polysaccharide-protein composite systems, TGase can synergize with genipin to construct interpenetrating networks, strengthening the gel mechanics and pH-responsive controlled-release performance, and a two-step enzymatic method can also be used for stepwise crosslinking to improve gel strength. This process is suitable for probiotic and heat-sensitive nutrient embedding and 3D printing bio-inks, but has shortcomings such as high enzyme cost, strong substrate specificity, and easy inactivation in complex systems. Existing improvement ideas combine composite processes such as ultrasonication and ionic crosslinking—first physically unfolding proteins to expose reaction sites, then enzymatically crosslinking—to simultaneously improve gel water-holding capacity and mechanical properties, broadening the application scenarios of food carriers.

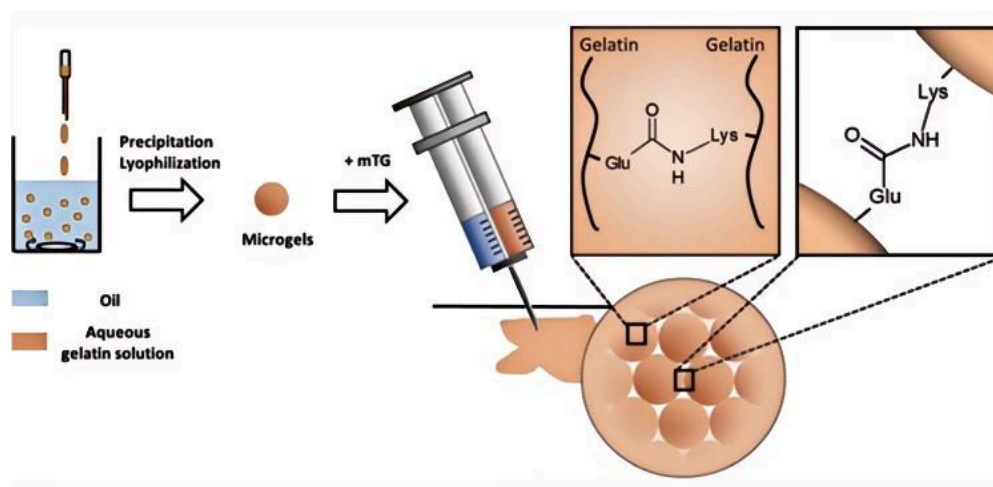


Figure 6. Schematic of hydrogel preparation by enzymatic crosslinking [20]

3. Characterization of hydrogels

3.1. Structure of hydrogels

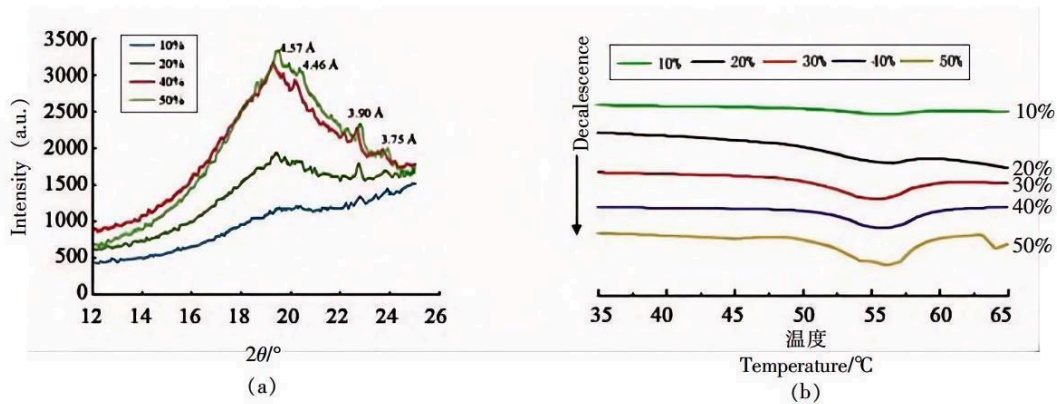
The core structure of a hydrogel is a three-dimensional network system formed by polymer substances through non-covalent bonds or crosslinking reactions, which can absorb and lock in large amounts of water while maintaining its own stable solid form [9]. Common natural hydrogel matrices include sodium alginate, ovalbumin, chitosan, etc.; hydrogels prepared from different raw materials show obvious differences in

internal structure. Taking sodium alginate hydrogel as an example, it can form a dense network structure through calcium ion crosslinking; the concentration of calcium ions directly changes the density of the gel network, thereby affecting the overall structural morphology [22]. Furthermore, as shown in the Table 1, the addition amount of TW-20 also has a significant impact on various texture parameters of the hydrogel. Ovalbumin fibril hydrogel, by contrast, relies on the self-assembly of protein molecules to form an ordered fibrous structure, and builds a uniform and stable three-dimensional network through intermolecular forces such as hydrogen bonds and hydrophobic interactions; the length and arrangement of the fibers can be regulated by temperature, pH, and stirring conditions.

Table 1. Effect of different Tween-20 additions on the textural properties of alginate bigel containing 50% oil phase [10]

Water absorption	Adhesive force/N	Viscosity/mJ	Adhesive toughness/N	Elongation at break/%	Degradation rate/%
0.50	0.93 ± 0.04^b	0.17 ± 0.01^c	0.40 ± 0.03^c	0.42 ± 0.02^c	0.93 ± 0.04^b
1	1.11 ± 0.05^a	0.25 ± 0.01^a	0.65 ± 0.04^a	0.52 ± 0.03^a	1.11 ± 0.05^a
2	0.98 ± 0.03^b	0.19 ± 0.01^b	0.48 ± 0.04^b	0.47 ± 0.03^b	0.97 ± 0.03^b

Note: Values in the same column with the same lowercase letter indicate no significant difference ($p > 0.05$).



XRD (a) and DSC (b) diffractograms of bigels with different oleogel content

Figure 7. XRD patterns of bigels containing different concentrations of oleogel [10]

In addition to single hydrogels, the currently widely studied bigel system is a biphasic structure compounded from hydrogel and oleogel; the two gel systems interpenetrate and complementarily fuse, retaining the hydrophilic network of the hydrogel while also possessing the lipid crystalline structure of the oleogel, with a richer structural hierarchy [23]. As shown in the Figure 7 and Table 2, characterization means such as XRD and scanning electron microscopy reveal that changes in oleogel content alter the crystal structure of the bigel; an increased oil-phase proportion leads to more crystals inside the gel and a denser structure, which is also the core reason why the hydrogel structure can be flexibly regulated. Overall, the structure of hydrogels is not fixed; precise regulation of the microstructure can be achieved by adjusting the raw material ratio, preparation conditions, and crosslinking method.

Table 2. Texture analysis of bigels containing different concentrations of oleogel [10]

Oleic acid percentage	Hardness/N	Adhesion/N	Viscous stress/Pa	Elastic stress/Pa	Fracture stress/Pa
10	2.22±0.08 ^a	0.06±0.00 ^c	0.07±0.02 ^d	1.10±0.06 ^a	2.22±0.08 ^a
20	1.55±0.09 ^b	0.12±0.03 ^d	0.12±0.06 ^d	0.75±0.04 ^b	1.53±0.09 ^b
30	1.28±0.11 ^c	0.15±0.01 ^c	0.26±0.05 ^c	0.63±0.07 ^c	1.27±0.12 ^c
40	1.05±0.04 ^d	0.19±0.00 ^b	0.45±0.05 ^b	0.48±0.02 ^d	1.05±0.04 ^d
50	1.10±0.04 ^d	0.10±0.04 ^a	0.67±0.11 ^a	0.49±0.01 ^d	1.09±0.04 ^d

3.2. Properties of hydrogels

The physicochemical properties of hydrogels directly determine their application scenarios, mainly including key indicators such as texture properties, rheological properties, freeze-thaw stability, and thermal stability, all of which can be intuitively characterized by simple experimental means [10]. In terms of texture properties, the hardness, stickiness, and gumminess of hydrogels are greatly affected by the raw material ratio and external conditions. For alginate bigel systems, as shown in Table 3, an increased calcium ion concentration significantly improves gel hardness and gumminess but reduces the gel's water-holding capacity; an increased oleogel content, by contrast, reduces gel hardness and improves stickiness, making the gel texture softer and smoother [24]. The addition of emulsifiers also fine-tunes the gel texture; an appropriate amount of Tween-20 makes the oil-water system fuse more uniformly and optimizes the overall gel texture.

Table 3. Effect of calcium ion addition on the textural properties of sodium alginate bigel [10]

Sodium stearate addition/%	Hardness/N	Adhesion/N	Viscosity/Pa	Elasticity/Pa	Fracture rate/%	Fracture stress/Pa
0.15	0.55±0.02 ^d	0.15±0.01 ^{ab}	0.43±0.07 ^a	0.28±0.01 ^c	6.61±0.03 ^a	0.5±0.06 ^d
0.30	1.03±0.05 ^c	0.18±0.01 ^a	0.41±0.03 ^b	0.49±0.02 ^c	6.58±0.05 ^a	1.02±0.06 ^b
0.60	2.11±0.04 ^b	0.12±0.03 ^{bc}	0.17±0.06 ^b	0.98±0.08 ^b	6.23±0.16 ^b	1.96±0.09 ^b
1.00	3.37±0.60 ^a	0.09±0.04 ^c	0.15±0.05 ^d	2.01±0.46 ^a	6.09±0.11 ^b	3.35±0.62 ^a

Note: Values in the same column with the same lowercase letter indicate no significant difference ($p > 0.05$).

Rheological property is one of the core characteristics of hydrogels; most hydrogels exhibit solid elastic characteristics under conventional conditions, with storage modulus always higher than loss modulus, maintaining a stable gel form. Temperature changes significantly affect their rheological properties; bigels with low oil-phase content have better thermal stability and can quickly recover the original structure after temperature rises and falls, while high oil-phase gels have poor thermal reversibility and are difficult to recover the initial state after high temperature. Freeze-thaw stability determines the low-temperature application ability of hydrogels; pure sodium alginate hydrogels have weak freeze-thaw resistance, while oil-water composite bigels can alleviate the damage of ice crystals to the gel network through oil-phase filling, greatly improving freeze-thaw stability and reducing water loss and structural stratification during low-temperature storage [8].

3.3. Functions of hydrogels

Relying on their unique structure and physicochemical properties, natural hydrogels possess multiple practical functions such as load protection, sustained-release delivery, antioxidant, and anti-inflammatory effects, with extremely high application value in food and biomedicine. First, the core function of hydrogels is the loading and delivery of bioactive substances; their porous network structure can encapsulate hydrophobic active components such as resveratrol and polyphenols, effectively solving the problems of poor water solubility, easy oxidation, and fast metabolism of such substances [25]. Hydrogels prepared from ovalbumin fibrils and sodium alginate have good biocompatibility, do not damage active components, and can slowly degrade in the gastrointestinal environment to achieve long-term sustained release of active substances, greatly improving their bioavailability. Second, hydrogels have good antioxidant and anti-inflammatory hepatoprotective functions. Resveratrol-loaded composite hydrogels can stabilize the activity of resveratrol by relying on the carrier structure, effectively scavenge free radicals in the body, inhibit oxidative stress responses, and at the same time regulate the endoplasmic reticulum stress pathway, alleviating alcohol-induced hepatocyte damage and liver inflammatory responses [25]. In addition, hydrogels can serve as excellent fat substitutes; in food processing, the bigel system can replace part of animal fat while retaining the soft and waxy taste of food, reducing the fat content of food and meeting healthy diet needs [26]. At the same time, their good water- and oil-holding capacities can effectively lock in moisture and oil inside food, avoid nutrient loss during processing and storage, and extend food shelf life, with high potential for food industrial application.

4. Applications of hydrogels

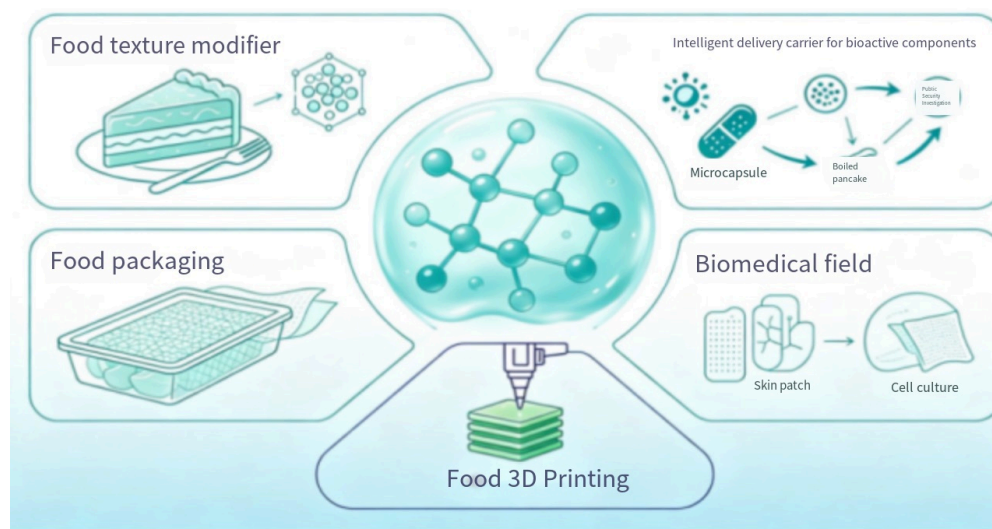


Figure 8. Application categories of hydrogels

In the fields of food and biomedicine, hydrogels have expanded into diverse applications due to their tunable network structures and stimuli-responsive properties. As shown in Figure 8, hydrogels can be used for food texture modification, delivery of bioactive compounds, smart food packaging, and food 3D printing, while also playing significant roles in biomedical applications such as wound dressings, tissue engineering, and targeted drug delivery. Different crosslinking methods endow hydrogels with distinct properties, enabling them to meet functional requirements across various applications.

4.1. As a food texture modifier

In modern food industry, food texture is a core indicator determining product mouthfeel, form stability, and consumer acceptance. With its unique three-dimensional network structure, excellent water retention, and rheological regulation ability, hydrogels have become green and efficient food texture modification materials [11]. Compared with traditional thickeners and stabilizers, protein-based and polysaccharide-based composite hydrogels can not only optimize the physical texture of food but also possess nutritional attributes and sustainability, fitting the current development trend of healthy food.

Plant-based food is the core application scenario of hydrogel texture modification. Hydrogels prepared from plant proteins such as soybean and pea proteins can accurately simulate the fiber structure, elasticity, and juiciness of animal muscle, effectively solving the industry pain points of loose mouthfeel and hard texture of traditional plant-based meat products; by regulating the hardness, elasticity, and water-holding parameters of hydrogels, vegetarian products with a mouthfeel close to real meat can be prepared [27]. At the same time, as shown in Figure 9, insoluble dietary fiber composite hydrogels such as those from square bamboo shoots can serve as food thickeners, emulsifiers, and gelling agents, significantly improving the texture uniformity and storage stability of sauces, dairy products, and baked foods, and inhibiting quality deterioration such as stratification and sedimentation during food storage [12].

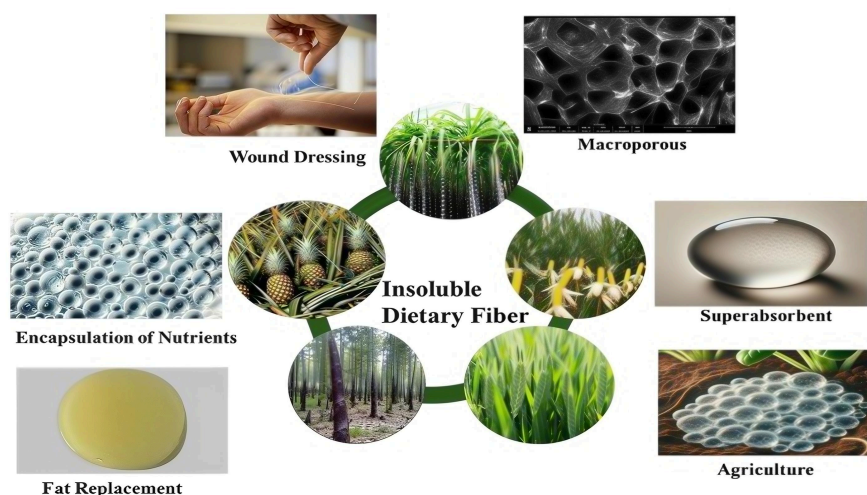


Figure 9. Dietary fiber-based hydrogel [12]

In addition, hydrogels can serve as green fat replacers to assist the development of low-fat healthy foods. Excessive intake of saturated fat easily causes chronic problems such as obesity and cardiovascular disease, but directly removing fat from food seriously destroys the lubricating mouthfeel and texture characteristics of the product. Polysaccharide-protein composite hydrogels can accurately simulate the lubricating texture and rheological properties of fat, greatly reducing the fat content of food while retaining the original mouthfeel, perfectly adapting to the development needs of healthy foods such as low-fat meat products and low-fat dairy products. At the same time, the tunable gel network structure can also create a special texture that dissolves upon entry into the mouth, adapting to the chewing and swallowing needs of special populations such as the elderly and infants, realizing the dual value of texture modification and functional adaptation [11].

4.2. As an intelligent delivery carrier for bioactive components

Bioactive components such as vitamins, polyphenols, probiotics, and functional peptides have excellent nutritional and health-care effects, but generally suffer from poor water solubility, weak oral stability, and susceptibility to destruction by acid-base environment, temperature, and enzymatic hydrolysis; when directly added to food or ingested by the human body, they are easily inactivated and have extremely low bioavailability [12]. With their three-dimensional porous network structure and controllable stimulus-responsive characteristics, hydrogels can serve as ideal intelligent delivery carriers, achieving effective encapsulation, long-term protection, and precise controlled release of bioactive components [28]. The protection mechanism of hydrogels mainly relies on physical entrapment and intermolecular forces to fix active components inside the gel network, effectively isolating adverse factors such as external high temperature, acidic environment, and digestive enzymes, and minimizing the loss of active components. Different from traditional embedding materials, intelligent responsive hydrogels have multiple responsive characteristics of pH, temperature, enzyme, and ionic strength, and can autonomously regulate the release rate and release location of active components according to environmental changes in application scenarios [27]. During food processing and storage, the gel structure can stably lock active components and avoid their oxidative inactivation; during human gastrointestinal digestion, it can respond to the acidic environment of the stomach to maintain structural stability and avoid degradation of active components by gastric acid, and after entering the intestine, it responds to the neutral environment to achieve targeted release, greatly improving the intestinal absorption rate and bioavailability of active components [11].

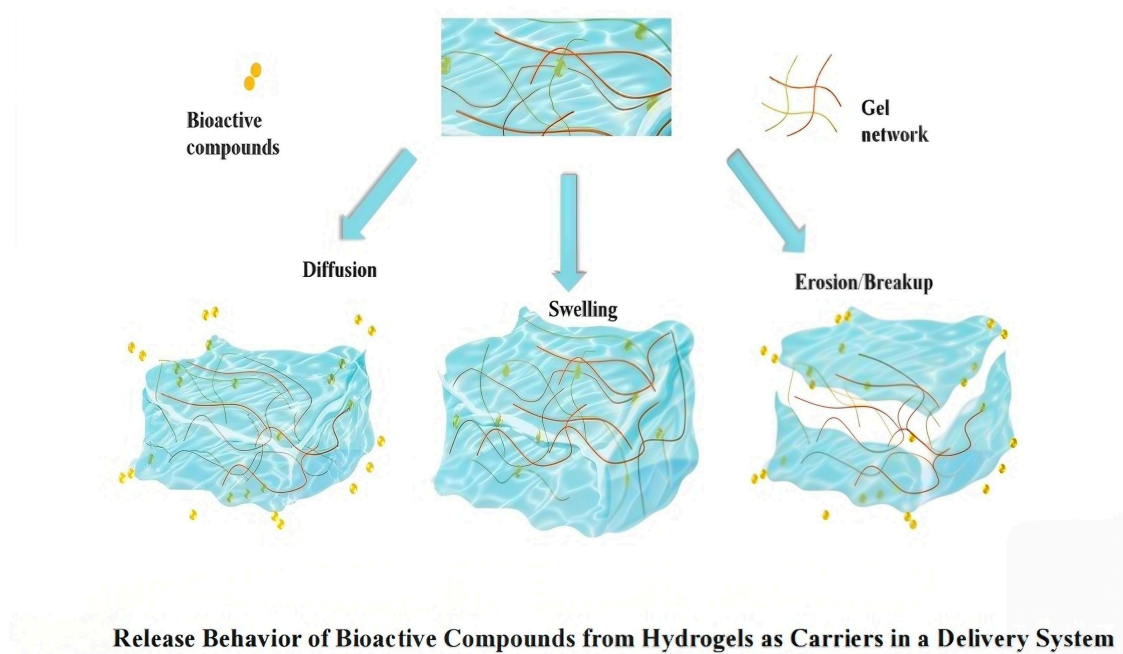


Figure 10. Schematic of bioactive substance release when hydrogels serve as delivery system carriers [12]

Polyphenol-based hydrogels perform particularly prominently in the delivery of active components; as shown in Figure 10, they can stably load antioxidant active components such as tea polyphenols, anthocyanins, and quercetin through dynamic crosslinking such as hydrogen bonds and coordination bonds, not only avoiding the oxidative inactivation of active components but also achieving long-term sustained

release [29]. Relevant studies show that sodium alginate/chitosan composite hydrogels can achieve intestinal targeted release of fucoxanthin, with a release rate of less than 3.8% in gastric fluid but up to 99% in the neutral intestinal environment, precisely realizing the directional delivery of active components [27]. At the same time, the delivery system is green, safe, and residue-free, fully adapting to the production and application requirements of functional foods and nutraceuticals.

4.3. As food packaging

Traditional plastic food packaging has defects such as difficult degradation, serious environmental pollution, and single function; it can only achieve basic water vapor and gas barrier functions and cannot meet the intelligent needs of food preservation and quality monitoring. Hydrogel-based smart active packaging materials, with the multiple advantages of degradability, antibacterial and antioxidant activity, and intelligent monitoring, are gradually replacing traditional packaging materials and have become a research hotspot in the field of food packaging, fitting the green and intelligent development direction of the food industry [3].

Hydrogels can construct functional active packaging systems by loading natural antibacterial and antioxidant active substances. As shown in Figure 11, Encapsulating natural functional components such as thymol, eugenol, tea polyphenols, and vitamin E in protein and polysaccharide-based hydrogel networks can effectively inhibit the reproduction of pathogenic bacteria on food surfaces and lipid oxidation through the sustained and controllable release of active substances, delay food spoilage, and significantly extend the shelf life of fruits, vegetables, meat products, and dairy products [28]. Compared with chemical preservatives, this system has no chemical residue and high safety, and does not affect the flavor and quality of the food itself. The slightly acidic electrolyzed water-hydrogel composite system has both high-efficiency antibacterial and long-term preservation effects, and can be widely used for the storage and preservation of fresh food [13].

Relying on intelligent responsive characteristics, hydrogels can also prepare visualized smart packaging to realize real-time monitoring of food quality. By embedding pH- and temperature-sensitive indicators such as anthocyanins and curcumin in the gel matrix, the packaging material can sense metabolites such as amines and carbon dioxide produced during food spoilage, and intuitively feed back food freshness through visible color changes [30]. This smart packaging does not require professional testing equipment; consumers can directly judge food quality with the naked eye, taking into account both preservation function and safety monitoring value. At the same time, polyphenol-based hydrogel packaging has excellent UV shielding and free-radical scavenging capabilities, which can further strengthen the food preservation effect, and the material can be naturally degraded, effectively solving the environmental pollution problem of traditional packaging.



Figure 11. Application of hydrogels in food packaging [3]

4.4. Biomedical applications

With excellent biocompatibility, low immunogenicity, bionic structure, and degradability, hydrogels have irreplaceable application value in the biomedical field, and have been widely used in wound care, tissue engineering, targeted drug delivery, disease treatment, and other scenarios, making them a research focus of new medical functional materials [2]. Compared with traditional medical materials, intelligent composite hydrogels can achieve functional synergy and precise response, greatly improving medical effect and safety.

Wound repair and antibacterial dressings are the most mature medical application scenarios of hydrogels. Studies show that composite hydrogels prepared by loading CS and PPy functional materials into PDA hydrogels can achieve synergistic antibacterial activity through charge adsorption and photothermal effects, rapidly kill bacteria under 808 nm laser irradiation, and at the same time have good biocompatibility, accelerating wound angiogenesis and tissue repair and inhibiting scar formation [2]. This type of hydrogel dressing can be recycled, does not induce bacterial resistance, and effectively solves the problems of single antibacterial effect and easy drug resistance of traditional antibacterial dressings, suitable for the care and repair of infectious wounds and burn wounds. Polyphenol-based hydrogels can also scavenge oxidative free radicals at the wound and regulate inflammatory responses, providing a new treatment scheme for diabetic refractory wounds [31]. As shown in Figure 12, in the intervention of ulcerative colitis (UC) with hyaluronic acid (HA)-based intelligent hydrogels, the hydrogel can target the inflammatory lesion relying on the CD44 receptor, prolong the colon residence time by its own adhesiveness, and at the same time exert physical barrier, anti-inflammatory, and immunomodulatory effects, regulating macrophage phenotype and repairing damaged intestinal mucosa. By constructing a pH, ROS, and enzyme multi-responsive system, site-specific drug release at the lesion can be achieved, reducing systemic side effects [32].

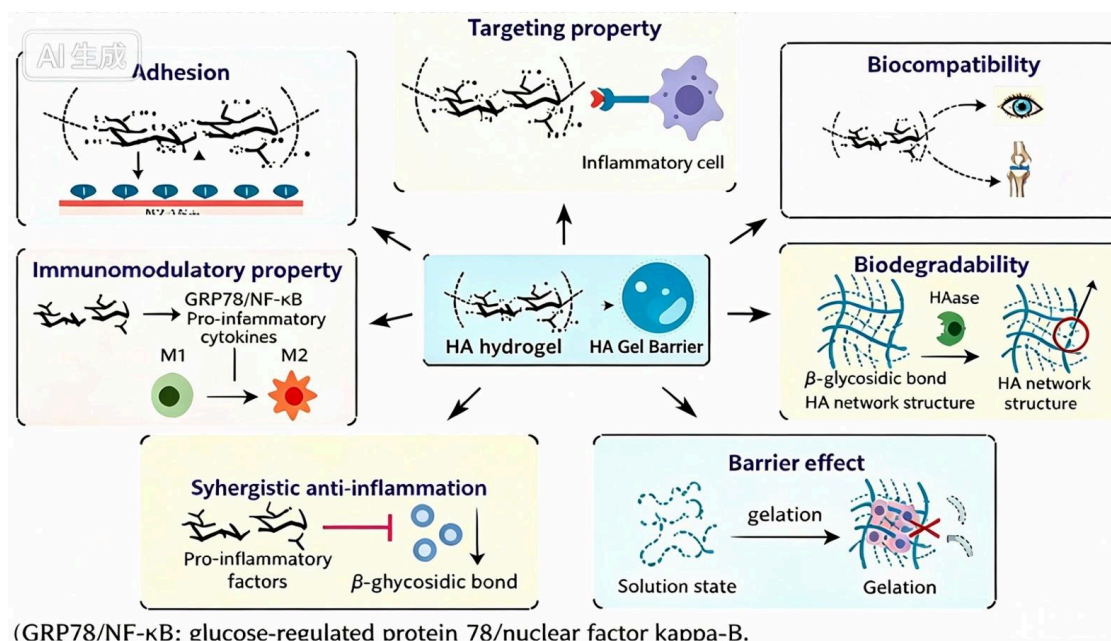


Figure 12. Advantages of HA hydrogel in alleviating UC [32]

Table 4. Core mechanisms and main functions of HA hydrogel in alleviating UC [32]

Advantages	Core Mechanism	Function
Adhesion	Electrostatic adsorption to the positively charged lesion surface	Prolongs hydrogel retention time in the colon
Targeting	HA binding to the CD44 receptor	Reduces damage to healthy intestinal tissue and systemic side effects, enabling precise treatment
Biocompatibility	Natural origin	Ensures safety for long-term use
Degradability	Enzymatic degradation	Avoids foreign-body residue
Barrier function	Gelation	Through sol–gel phase transition, forms a protective physical barrier on the lesion mucosa that isolates pathogenic bacteria
Synergistic anti-inflammatory effect	Regulation of inflammatory cytokines	Directly or indirectly suppresses the release of inflammatory mediators, exerting anti-inflammatory effects
Immunomodulation	GRP78/NF-κB	Drives macrophage polarization from the M1 to the M2 phenotype

In the field of tissue engineering and bone regeneration, the bionic three-dimensional structure of hydrogels can accurately simulate the extracellular matrix environment of the human body, provide a good carrier for cell adhesion, proliferation, and differentiation, and effectively promote the repair and regeneration of bone and cartilage tissues [2]. Their low immune response, high water absorption, and degradability can avoid the body rejection caused by implanted materials, adapting to the repair treatment of bone defects and cartilage injuries. As shown in Table 4, hydrogels can serve as intelligent drug delivery carriers, achieving targeted sustained release of drugs according to microenvironment changes such as pH and ROS concentration at the lesion site of the human body, improving drug utilization and reducing systemic toxic side effects, showing great application potential in cancer treatment and inflammatory disease treatment [32]. In addition, modified hyaluronic acid intelligent hydrogels can accurately adapt to the lesion microenvironment of ulcerative colitis, achieve intestinal targeted drug delivery and wound repair, and provide new material support for the treatment of digestive tract diseases.

4.5. Application in food 3D printing

Food 3D printing is a new personalized food processing technology that can achieve precise forming of complex-structure foods through digital modeling, and the performance of printing consumables is the core bottleneck restricting the development of this technology. With controllable rheological properties, self-supporting ability, and printability, hydrogels have become high-quality 'bio-inks' for food 3D printing, effectively solving the problems of poor formability, easy structural collapse, and insufficient precision of traditional printing consumables, and promoting the upgrading of food processing toward personalization, precision, and intelligence [11].

After structural reinforcement modification, natural polysaccharide and protein-based hydrogels have excellent shear-thinning characteristics; they can flow with extrusion pressure during printing and quickly

recover the gel structure after printing, ensuring the form stability and forming precision of printed products [3]. Compared with traditional printing raw materials such as flour and fruit and vegetable puree, hydrogel bio-inks can precisely regulate parameters such as hardness, elasticity, and swelling, and can prepare foods with complex structures and regular shapes, adapting to diversified food design needs [33]. At the same time, such inks are safe and edible raw materials, and can directly load nutrients such as vitamins, dietary fiber, and functional polyphenols, realizing the integrated processing of food forming and nutritional fortification.

The core advantage of food 3D printing hydrogels lies in the realization of personalized food customization, which can accurately adapt to the dietary needs of special populations. By regulating the gel texture characteristics, foods that dissolve easily in the mouth and have a soft texture can be prepared to meet the eating needs of patients with dysphagia, the elderly, and infants; according to the nutritional needs of different populations, nutrients can be precisely proportioned to customize exclusive functional foods [11]. In addition, reinforced polysaccharide hydrogels can effectively improve the precision and stability of 3D printing, expand the research and development space of new foods such as plant-based meat, artificial vegetarian food, and functional snacks, and provide a new technical path for food intelligent manufacturing and personalized nutrition supply. Dai et al. used nanofiber-reinforced guar gum hydrogel and successfully prepared hydrogel films by 3D printing technology [34]. Studies show that the tensile strength and breaking strength of the reinforced hydrogel film are much higher than those of the unreinforced hydrogel film. They also used this hydrogel film as packaging for fresh mooncakes. As shown in Figure 13, the experimental results indicate that the reinforced hydrogel film is not only oil-resistant but also maintains the freshness of the mooncakes [13].

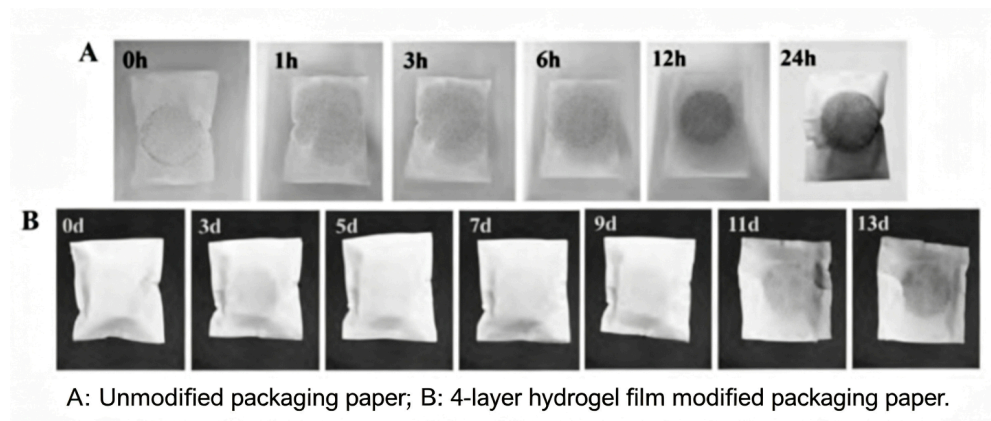


Figure 13. Pictures of different mooncake packaging paper bags under different placement times [13]

5. Conclusion

With the rapid development of the big health industry and green material technology, natural polymer hydrogels, with the core advantages of safety, non-toxicity, tunable properties, and good biocompatibility, are gradually replacing traditional chemical materials and showing irreplaceable application value in the food industry and biomedicine; new crosslinking technologies and intelligent modification means continuously drive the iterative upgrading of hydrogel materials, with broad research and industrialization prospects. This paper systematically combs the complete research system of hydrogels, covering the three core sections of preparation technology, characterization technology, and diverse applications, and summarizes as follows. First, hydrogel preparation technology has formed a physical, chemical, and biological multi-dimensional system; the five mainstream preparation processes each have their own advantages and disadvantages, with

significantly differentiated adaptation scenarios, and composite crosslinking technology has become a key means to compensate for the defects of a single process and improve the comprehensive performance of gels. Second, the hydrogel characterization technology system is increasingly complete; through the three-dimensional characterization of structure, properties, and function, the structure-property-function correspondence of materials can be accurately revealed, providing a quantitative basis for gel performance regulation and application optimization. Furthermore, hydrogel application scenarios are highly diversified: in the food industry, texture modification, active substance delivery, smart fresh-keeping packaging, and customized 3D printing production can be realized, while in the biomedical field, wound repair, tissue regeneration, and targeted drug delivery can be applied. At present, hydrogel research still has many shortcomings: insufficient mechanical stability of physical gels, safety hazards of chemical gels, and high cost of enzymatic crosslinking processes restrict their large-scale application. Future industry development will focus on three directions—the research and development of clean-label composite crosslinking technology, the creation of multi-stimulus-responsive intelligent gels, and the industrial application of green bio-inks—continuously breaking through technical bottlenecks and promoting the in-depth development of hydrogel materials toward greening, intelligence, and industrialization.

References

- [1] Nie, K. L., Hu, F. Y., Sun, Q., Bai, R. H., & Huang, Y. (2026). Research progress on preparation methods, formation mechanisms, and food applications of polysaccharideprotein composite hydrogels. *Food and Fermentation Industries*. Advance online publication. <https://doi.org/10.13995/j.cnki.111802/ts.044784>
- [2] Wu, L. E., Zhou, X. Y., Cheng, W., et al. (2025). Current applications and future developments in biomedical hydrogels. *Journal of Shenyang Pharmaceutical University*, 42(2), 121130. <https://doi.org/10.14066/j.cnki.cn211349/r.2023.0281>
- [3] Xu, R. Q., Man, W. J., Li, G. X., Feng, D., Ma, M. H., Fan, J. Y., Li, M. J., Wang, J., & He, X. Y. (2026). Recent advances in the fabrication methods, characterization techniques, and application research of proteinbased hydrogels in the food industry. *Science and Technology of Food Industry*. Advance online publication. <https://doi.org/10.13386/j.issn10020306.2025120103>
- [4] Zuo, X. B., Kong, J. H., Zhao, L. H., et al. (2025). Progress in the preparation and application research of polyphenolic hydrogels. *CIESC Journal*. <https://link.cnki.net/urlid/11.1946.tq.20251121.1006.002>. <https://doi.org/10.11949/04381157.20251017>
- [5] Hu, X. F., Li, W. Z., He, Y., et al. (2026). Preparation of sodium alginate/starch acetate hydrogel beads and optimization of folic acid loading. *China Food Additives*(4), 9097. <https://doi.org/10.19804/j.issn10062513.2026.4.011>
- [6] Zeng, X. L. (2025). *Preparation of curcumin starch hydrogel and its application in noodle processing* [Doctoral dissertation]. Yangzhou University, Yangzhou.
- [7] Yang, M. Q. (2025). Preparation of quercetin and resveratrol coencapsulated hydrogel beads and their application in jelly [Doctoral dissertation]. Nanchang University, Nanchang.
- [8] Yu, K. J., Zhang, S. Y., Nie, Y. C., et al. (2024). Preparation and characterization of nanocellulose hydrogel and its application for preservation of fresh pork. *Transactions of the Chinese Society of Agricultural Engineering*, 40(13), 253–261. DOI:10.11975/j.issn.1002-6819.202311181.
- [9] Zhou, Y. L., Wang, Y. G., & Lu, S. M. (2025). Preparation and characterization of cinnamic acid composite hydrogel and its antibacterial activity against *Alicyclobacillus acidoterrestris*. *Food Science and Technology*, 50(10), 284–293. DOI:10.13684/j.spkj.1005-9989.2025.10.034.
- [10] Yang, J. Y., Zheng, H. X., Gao, Y. X., et al. (2022). Preparation and physicochemical properties of bigel based on alginate hydrogel and glycerin monostearate oleogel. *Journal of Chinese Institute of Food Science and*

- Technology*, 22(10), 97–107. DOI:10.16429/j.1009-7848.2022.10.011.
- [11] Shi, J. M., Zhang, Y., Yu, F. L., et al. From molecular cross-linking to functional performance: Applications and challenges of protein-based hydrogels in the food industry. *Food Science*. [2026-02-12]. <https://link.cnki.net/urlid/11.2206.TS.20260211.1640.029>. DOI:10.7506/spkx1002-6630.20221128-238.
 - [12] Chen, Y. (2025). Construction and application of composite hydrogels based on insoluble dietary fiber from Fang bamboo shoots [Doctoral dissertation]. Guizhou University, Guiyang.
 - [13] Wang, Y. C., Li, J., Mao, L. K., et al. Network structure strengthening and application of natural polysaccharidebased hydrogels. *China Food Additives*, 2025(10), 1525. DOI:10.19804/j.issn10062513.2025.10.003.
 - [14] Chen, X. T., Lu, C., Wang, Z. H., et al. Progress in preparation methods and applications of composite hydrogels. *Liaoning Silk*, 2025(4), 4042.
 - [15] Kim, S. H., Kim, K., Kim, B. S., et al. Fabrication of polyphenol-incorporated antiinflammatory hydrogel via high-affinity enzymatic crosslinking for wet tissue adhesion. *Biomaterials*, 242, 119905.
 - [16] Bashir, S., Hina, M., Iqbal, J., et al. Fundamental concepts of hydrogels: Synthesis, properties, and their applications. *Polymers*, 12(11), 2702.
 - [17] Sobczak, M. Enzyme-responsive hydrogels as potential drug delivery systems: State of knowledge and future prospects. *International Journal of Molecular Sciences*, 23(8), 4421.
 - [18] You, M. K., Zhang, H. H., Zhang, Z. H., et al. (2025). Preparation and properties of ioncrosslinked nanocomposite highstrength hydrogels. *Acta Materiae Compositae Sinica*, 42(8), 41254136.
 - [19] Chen, J., Wang, Y., Pu, M., et al. (2025). pH-regulated preparation and structural characterization of non-covalent complexes of soybean isolate proteins with different charged polysaccharides. *International Journal of Biological Macromolecules*, 298, 140004.
 - [20] Li, X., Möller, M., Kessler, H., et al. (2020). Injectable macroporous hydrogel formed by enzymatic crosslinking of gelatin microgels. *Acta Biomaterialia*, 113, 224235.
 - [21] Asamoah, S., Pravda, M., Matonohová, J., et al. (2025). Iron (ii)-catalysed tyrosinase crosslinked hyaluronic acid hydrogel for the controlled release of human antibodies. *Journal of Materials Chemistry B*, 13(23), 6804–6818.
 - [22] Mokhtari, S., Jafari, S. M., Assadpour, E. (2017). Development of a nutraceutical nano-delivery system through emulsification/internal gelation of alginate. *Food Chemistry*, 229, 286-295.
 - [23] Michele, L. D., Fiocco, D., Varrato, F., et al. (2014). Aggregation dynamics, structure, and mechanical properties of bigels. *Soft Matter*, 10(20), 3633-3648.
 - [24] Zhang, Y. Q., Yu, Y. C., Lu, Y. Y., et al. (2006). Effect of Ca²⁺ concentration on the viscosity of dilute alginate solution. *Chinese Journal of Applied Chemistry*(11), 1259-1263.
 - [25] Wang, Y. R. (2024). Preparation, characterization and hepatoprotective activity of ovalbumin fibril-chitosan-resveratrol self-assembling hydrogel [Doctoral dissertation]. Hefei University of Technology, Hefei.
 - [26] Feng, Y. Y., Xu, J. X., Yu, D., et al. (2019). Recent advances in the application of emulsion gels as fat replacers in meat products. *Food Science*, 40(21), 236–242.
 - [27] Liu, X., Ma, B., Chen, Z., & Li. (2015). Research progress on plant-based meat products: Functional properties of raw materials, structural reconstruction technologies, safety evaluation systems, and future challenges. *Modern Food Science and Technology*, 41(10), 125–135. <https://doi.org/10.13982/j.mfst.1673-9078.2025.10.1001>.
 - [28] Aman Mohammadi, M., Dakhili, S., Mirza Alizadeh, A., et al. (2024). New perspectives on electrospun nanofiber applications in smart and active food packaging materials. *Critical Reviews in Food Science and Nutrition*, 64(9), 2601–2617. <https://doi.org/10.1080/10408398.2022.2124506>.
 - [29] Zhao, M., Han, P., Mu, H., et al. (2025). Food packaging films from natural polysaccharides and protein hydrogels: A comprehensive review. *Food Chemistry: X*, 25, 102174. <https://doi.org/10.1016/j.fochx.2025.102174>.

- [30] Wang, Y., Shu, H. T., Bao, Y. W., et al. (2026). Research progress on hydrogel-based substrates for surface-enhanced Raman spectroscopy in detection of foodborne pathogenic bacteria. *Modern Food*(6), 192–199. <https://doi.org/10.16736/j.cnki.cn41-1434/ts.2026.6.055>.
- [31] Qi, X. L., Tong, X. Q., You, S. Y., et al. (2022). Mild hyperthermia-assisted ROS scavenging hydrogels achieve diabetic wound healing. *ACS Macro Letters*, 11(7), 861–867.
- [32] Hu, J. X., Zhu, Z. B., Gu, H. F., et al. (2026). Research advances on preparation of intelligent hyaluronic acid hydrogels and its application in ulcerative colitis. *Food Science*, 47(15). DOI:10.7506/spkx1002663020260202013.
- [33] Guo, C., Zhang, M., & Bhandari, B. (2019). Model building and slicing in food 3D printing processes: A review. *Comprehensive Reviews in Food Science and Food Safety*, 18(4), 1052–1069. <https://doi.org/10.1111/1541-4337.12443>.
- [34] Dai, L., Xi, X. J., Li, X. Y., et al. (2021). Self-assembled allpolysaccharide hydrogel film for versatile paper-based food packaging. *Carbohydrate Polymers*, 271, 118425.