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**Review Paper**

# Hydrogels: sources and applications-an overview

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## ABSTRACT

Hydrogels are crosslinked three-dimensional polymer network materials with hydrophilic structures that can absorb and retain large amounts of water and/or biological fluids without dissolving, owing to the physical and chemical nature of their crosslinks. They play significant roles in various industrial and environmental applications. In many applications, natural hydrogels have gradually been replaced by synthetic hydrogels because of their superior water absorption capacity, longer lifetime, and diverse sources of raw chemical materials. The main functions of hydrogels are important and diverse, including high water absorption and retention, controlled drug delivery, biocompatibility, soft-tissue-mimicking behavior, swelling and deswelling ability, selective permeability, mechanical support, and environmental remediation. Hydrogels are commonly classified according to their origin, composition, crosslinking type, responsiveness, and structure. They have different applications, particularly in biomedical and healthcare fields, hygiene and personal care products, industrial and engineering applications, agriculture, environmental remediation, and nanotechnology. The literature on hydrogels has expanded considerably, especially in scientific research fields. Therefore, this review examines various publications and technical reports focusing on hydrogel products from an engineering perspective to summarize the technological dimensions of this rapidly advancing multidisciplinary research field. This review aims to summarize and evaluate the preparation, classification, and recent applications of hydrogels, emphasizing their transition from simple water absorbing materials to tailored smart systems. It also highlights the relationship between structural design and functional performance in different sectors, such as drug delivery, wound healing, oil-water separation, and agricultural water management. Finally, the review addresses current challenges and proposes future research directions to improve hydrogel stability, responsiveness, and biocompatibility.

**Keywords:** *Biomedical applications, Environmental uses, Hydrogel, Nanocomposite, Smart materials*

## 1 INTRODUCTION

The recent development of hydrogels as functional biomaterials has transformed research on responsive materials. Hydrogels were initially developed for biological applications, including tissue scaffolds and contact lenses [1]. They were first described in the late nineteenth century as colloidal gels prepared from inorganic salts. However, one of the earliest widely recognized synthetic hydrogels was reported in 1960, when Wichterle and Lim prepared poly(2-hydroxyethyl methacrylate) and used it in the contact lens industry because of its ability to absorb moisture while retaining its network structure [2].

Hydrogels have a unique three-dimensional crosslinked polymer network that enables them to absorb and retain large amounts of water within their structure while maintaining the swollen network form. This property is mainly attributed to the presence of polar hydrophilic functional groups, such as $-SO_3H$, $-OH$, $-NH_2$, $-COOH$, and $-CONH_2$, within or

adjacent to the polymer matrix [3]. Hydrogels are soft materials composed of water molecules and hydrophilic polymer networks. Their high water content, which may exceed 95% by weight, enables them to dissolve and transport ions and many small molecules. Because their polymer networks are generally weakly crosslinked, hydrogels are usually soft and flexible.

Hydrogels are also found widely in nature and may have existed since the early stages of life on Earth. Natural hydrogel-like structures are present in several biological systems, including xylem and phloem in plants, as well as muscle and cartilage in animal tissues [4]. Compared with metals, ceramics, and many other polymeric materials, hydrogels are relatively recent additions to industrial applications. Their wide variety, ranging from natural to synthetic forms with diverse polymer structures and chemical compositions, makes them highly versatile and suitable for numerous uses [5, 6].

Functional hydrogels can mimic biological tissues chemically, mechanically, and electrically. Established medical applications of functional hydrogels include tissue engineering, wound dressings, contact lenses, and drug delivery systems [7–10]. Hydrogels also play an important role in stretchable devices and soft robotics, such as artificial muscle-like actuators, hydrogel-based soft devices, soft displays, stretchable skin-like sensors, and axon-like conductive connections. These applications are supported by the remarkable properties of smart hydrogels, including reversible swelling and deswelling behavior, environmental responsiveness, high ionic conductivity, permeability, and tunable surface characteristics.

One of the key challenges in hydrogel applications is achieving durable bonding between hydrogels and other materials. Hydrogels have long been studied as adhesives for wound healing; however, for decades, their adhesion strength remained limited to less than 10 $J/m^2$ [11]. Yang et al. made a significant advancement by adhering hydrogels to non-porous surfaces and elastomers with adhesion energies above 1000 $J/m^2$. This strong adhesion was achieved through two combined effects: covalent bonding between polymer networks and sacrificial bonds within the hydrogel that dissipate energy from the substrate. Since these findings were reported, several techniques have been developed to achieve strong hydrogel adhesion, including the use of biodegradable polymer chains to stitch wet materials, such as tissues and hydrogels, together [12].

Ganji et al. [13] suggested that hydrogel swelling involves a complex multistage process. In the first stage, the polar groups of the hydrogel matrix are hydrated by water molecules. In the second stage, water interacts with exposed hydrophobic groups, forming secondary bound water. The total bound water therefore includes both primary and secondary bound water. In the third stage, the osmotic driving force of the network, which tends toward infinite dilution, is counteracted by physical or chemical crosslinks, leading to the absorption of additional water. The water incorporated during the equilibrium swelling phase is referred to as bulk or free water, which occupies the spaces between polymer chains and within larger pores. The amount of water that a hydrogel can absorb is influenced by temperature and by specific interactions between water molecules and polymer chains, a phenomenon that can be explained by the Flory-Huggins theory.

Hydrogels can be produced using various modern chemical techniques. These include single-step methods, such as simultaneous polymerization and crosslinking of multifunctional monomers, as well as multistep methods involving the synthesis of polymer molecules containing reactive groups followed by crosslinking with suitable crosslinking agents. Polymer engineers can design and prepare polymer networks with precise molecular control over structural characteristics, such as crosslinking density, enabling adjustment of biodegradability, mechanical strength, and responsiveness to chemical and biological stimuli. Identifying polymer combinations that respond to multiple stimuli, including physical, chemical, and biological signals, is considered important for the development of advanced hydrogel systems.

Further research is needed to develop hydrogels with improved responsiveness, mechanical properties, and stability for biomedical and industrial applications. For example, additional studies on the copolymerization of polyacrylamide with other monomers are needed to improve the mechanical strength and hydrolytic stability of polyacrylamide hydrogels. Although hydrogels are highly versatile materials with rapidly expanding literature, future progress depends on overcoming persistent limitations, such as low mechanical strength, limited water flux, and challenges in translating laboratory-scale advances into practical, durable, and widely applicable systems [14].

Therefore, this review provides a comprehensive overview of hydrogel sources, classifications, and applications, with particular emphasis on recent advances in smart and nanocomposite hydrogels. The main aim is to

bridge the gap between earlier studies that focused mainly on basic swelling behavior and recent research investigating multifunctional and stimuli-responsive systems. This review focuses on hydrogel sources, classification, and major applications in different fields.

## 2 SOURCES OF HYDROGELS

Hydrogels can be classified into two main groups according to their origin: natural hydrogels and synthetic hydrogels [3].

### 2.1 Natural hydrogel

Hydrogels obtained from natural polymers are classified as natural polymer hydrogels. Polysaccharides, polynucleotides, and polypeptides are examples of naturally occurring polymers used in hydrogel preparation. Natural polymers can be neutral, cationic, or anionic and may be derived from various natural sources. These polymers possess several desirable biological properties, including availability, abundance, low cost, nontoxicity, and recyclability [15].

The relationship between structure and function has attracted the interest of many researchers, especially in naturally occurring bioactive materials. In recent decades, advances in structural and functional materials have increased the development of natural polymers for biomedical applications [16]. Natural polymers have distinct macromolecular structures composed of covalently linked monomeric units. Natural polymer hydrogels have numerous biomedical applications, including tissue engineering, wound healing, and controlled or targeted drug delivery [17]. However, later studies introduced synthetic alternatives to overcome some limitations of natural hydrogels, which are often associated with low mechanical strength and instability.

### 2.2 Synthetic hydrogel

Synthetic polymers have more predictable physical and chemical properties than natural polymers, making them suitable for hydrogel preparation. Synthetic polymers may have long-chain structures and high molecular weights. However, synthetic hydrogels are generally less biologically active than natural hydrogels. Polymer hydrogels can be prepared using several methods, including vinyl monomer polymerization and chemical crosslinking of polymers. Hydrogels are produced from various synthetic polymers, including PVA, PEG, PEO, PHEMA, PAA, and PAAm [18, 19].

Ramzan et al. reported a glycerin-based poly(acrylic acid) hydrogel network prepared by polymerization of acrylic acid in the presence of benzoyl peroxide and Novozyme 435 under neutral, acidic, and basic pH conditions [20]. Takada et al. prepared hydrogel slabs and cylinders of poly(2-hydroxyethyl methacrylate-co-methacrylic acid) by free-radical bulk polymerization. Hydrogel slabs were prepared using a redox system of ammonium persulfate and sodium metabisulfite as initiators, with TEGDMA as the crosslinking agent. Hydrogel cylinders were synthesized using AIBN as an initiator. The release of phenylpropanolamine was examined at different pH values using a desorption method [21].

Khan et al. prepared poly(acrylic acid) hydrogels using ammonium persulfate, $(NH_4)_2\ S_2O_8$, as an initiator and N,N'-methylene bisacrylamide (MBAA) as a crosslinking agent [22]. Saberian et al. prepared polyacrylamide hydrogels using chemical radical initiation and gamma irradiation at $0.72 kGyh^{-1}$ with three different crosslinking agents. The swelling ratios of the prepared gels ranged from 255% to 1450%, depending on the synthesis method, crosslinking agent, and concentration [23].

Kesharwani et al. developed self-healing clay-crosslinked polyacrylamide hydrogels using a radical method. Polyacrylamide hydrogels are characterized by low hydrolytic stability and mechanical strength; therefore, copolymerization with additional monomers can improve their properties. Poly(acrylamide-co-acrylic acid) hydrogels have been prepared using free-radical polymerization, and rheological studies showed that these copolymer hydrogels possess improved mechanical strength [24].

Fathi et al. developed temperature- and pH-responsive hydrogels using poly(N-isopropylacrylamide-co-itaconic acid) combined with chitosan. These hydrogels were prepared by mixing poly(N-isopropylacrylamide-co-itaconic acid) with chitosan and using glycerophosphate as an ionic crosslinking agent. Poly(N-isopropylacrylamide)-based hydrogels exhibit temperature sensitivity and have shown potential for drug-delivery applications [25].

Tuan and Nhu used free-radical polymerization to prepare poly(N,N-diethylacrylamide) and poly(N-isopropylacrylamide) hydrogels. They compared their swelling, deswelling, reswelling, insulin storage, and controlled-release properties. PNDEAM hydrogels showed greater dependence on the crosslinking agent, longer reswelling kinetics, and faster insulin release than PNIPAM hydrogels [26]. Agnihotri et al. developed semi-interpenetrating polymer network chitosan-

poly(acrylamide-co-ethylene oxide) hydrogel microspheres. Poly(acrylamide-co-ethylene oxide) was prepared by free-radical polymerization and embedded within glutaraldehyde-crosslinked chitosan hydrogels. These hydrogel microspheres were used for encapsulation and delivery of anticancer drugs [27].

## 3 CLASSIFICATION OF HYDROGEL

Hydrogels can be classified according to several criteria, as described below.

### 3.1 Classification according to polymeric composition

The preparation process leads to several major types of hydrogels, including the following:

1. **Homopolymeric hydrogels:** These hydrogels are prepared from a single monomer species that forms the basic structural unit of the polymer network [28]. Homopolymers may have crosslinked backbone structures depending on the monomer type and polymerization method.

2. **Copolymeric hydrogels:** These hydrogels contain two or more different monomer types, at least one of which is hydrophilic. The monomers may be arranged randomly, alternately, or in block patterns along the polymer network chain [29].

3. **Interpenetrating polymer network hydrogels:** Multipolymer interpenetrating polymer network (IPN) hydrogels are composed of two separate crosslinked synthetic or natural polymer components arranged within one network. Semi-IPN hydrogels contain both crosslinked and non-crosslinked polymer components [30].

### 3.2 Classification based on type of cross-linking

Hydrogels are divided into two main types according to their crosslinking nature: chemically crosslinked and physically crosslinked networks. Chemically crosslinked hydrogels form permanent connections through covalent bonds between polymer chains, providing high mechanical strength and structural stability, even under harsh environmental conditions. These hydrogels are typically synthesized using crosslinking agents, radiation, or photopolymerization methods. However, they are often less reversible and may require specific degradation mechanisms for biomedical applications.

Physically crosslinked hydrogels rely on non-covalent interactions, such as hydrogen bonding, ionic interactions, hydrophobic associations, or polymer-chain entanglements. These interactions are temporary and reversible, allowing the hydrogel to respond dynamically to environmental stimuli, such as pH, temperature, or ionic strength. This feature makes physically crosslinked hydrogels suitable for smart or stimuli-responsive systems used in controlled drug delivery, tissue engineering, and wound healing. In some cases, hybrid hydrogels combine chemical and physical crosslinking to achieve a balance between mechanical integrity and flexibility, thereby improving performance in biomedical and environmental applications [30].

### 3.3 Classification based on configuration

Hydrogels can also be classified according to their physical structure and chemical composition as follows:

1. Amorphous, or non-crystalline, hydrogels.

2. Semicrystalline hydrogels, which contain both amorphous and crystalline phases.

3. Crystalline hydrogels.

### 3.4 Classification based on physical appearance

The physical form of hydrogels, such as matrix, film, or microsphere, is influenced by the polymerization method used during preparation.

### 3.5 Classification according to network electrical charge

Hydrogels can be classified into four groups according to the presence or absence of electrical charge on the crosslinked polymer chains:

1. Nonionic, or neutral, hydrogels.

2. Ionic hydrogels, including anionic or cationic hydrogels.

3. Amphoteric electrolyte, or ampholytic, hydrogels containing both acidic and basic groups.

4. Zwitterionic, or polybetaine, hydrogels containing both anionic and cationic groups in each structural repeating unit.

Synthetic hydrogels have gradually replaced natural hydrogels in some applications because of their superior water-retention ability, longer lifetime, and greater availability of chemical raw materials. This indicates that natural hydrogels have limitations in certain applications compared with synthetic counterparts. For example, polyacrylamide hydrogels have low hydrolytic stability and mechanical strength, and improving these properties often requires copolymerization with additional monomers.

Hydrogels are commonly used for oil-water separation, but their nanoscale network size, approximately 10 nm , may result in insufficient water flux, usually less than 30 L $m^{-2}$ $h^{-1}$ bar $^{-1}$ [14]. In food packaging, biopolymers have lagged behind pharmaceutical materials because of their high cost, low strength, and poor water resistance. To overcome these limitations, natural and synthetic polymers are often combined, or organic additives are incorporated. Another major challenge in hydrogel applications is forming durable bonds with other materials. For decades, hydrogels used as wound-healing adhesives showed adhesion energies of less than 10 J $m^{-2}$. Despite their potential, nanocomposite hydrogels remain limited in food-science applications. Although the literature on hydrogels is expanding, this review focuses specifically on technological aspects from an engineering perspective, suggesting a need for broader cross-disciplinary reviews [11]. Future research should focus on improving hydrogel performance, reducing design complexity, and expanding applications, particularly in biomedical and advanced engineering fields.

## 4 APPLICATION OF HYDROGEL

Hydrogels have extensive applications in engineering, biology, and pharmaceutical sciences. Polyelectrolyte hydrogels are used in drug delivery, delivery of proteins and peptides, pesticide and nutrient release, hormone delivery, agriculture, horticulture, biotechnology, cell scaffolding, pharmaceuticals, and biomedical fields. Cationic polymers are frequently used as synthetic carriers because they can condense large structures and protect negatively charged DNA. Therefore, they are useful in cell transfection, gene therapy, bile acid sequestration, and the development of viral and non-viral vectors for the delivery of DNA and oligonucleotides. Hydrogels can respond rapidly to environmental changes, including variations in electric and magnetic fields, pH, ionic strength, and temperature, resulting in substantial volume changes [31].

### 4.1 Biomedical applications

Hydrogels can mimic the behavior of human tissues in response to environmental conditions such as pH, temperature, enzymes, and electric fields. They are used in medical implants, artificial muscles, robotic grippers, diagnostic devices, bone implant stabilization, reduction of intimal thickening in animal models, and thrombosis reduction [32, 33]. Hydrogel coatings in urinary catheters can reduce bacterial colonization and provide a smooth, slippery surface that improves biocompatibility. Park et al. reported advanced applications of hydrogels [34]. Artificial muscles can be developed by converting electrochemical stimuli into mechanical work, allowing reversible contraction and relaxation under physicochemical stimulation. These artificial muscles function similarly to human muscles but are powered electrically.

#### 4.1.1 PEG–PLGA-based hydrogels

Khalil et al. developed PEG–PLGA graft copolymer hydrogels for cancer treatment and imaging [35]. These hydrogels use light-sensitive polymers with stimuli-responsive properties, making them suitable for biomedical applications. An effective delivery system should be able to cross cell membranes, target specific tissues, facilitate nuclear uptake, prevent enzymatic degradation and aggregation, and deliver genetic material without causing toxicity or immune responses. Hydrogels have a wide range of applications under controlled conditions, highlighting their smart behavior and potential for use in several research areas [36].

#### 4.1.2 PPO–PEO-based hydrogels

Curvello et al. reported that PPO–PEO hydrogels form transparent gels at body temperature, fill wound spaces, and help prevent bacterial infection [37]. These hydrogels are flexible, durable, and permeable to water vapor and metabolites, making them suitable for wound dressing. Hydrogels are also used in contact lenses and intraocular lenses. Soft intraocular hydrogel lenses offer higher oxygen permeability than rigid lenses, but they may cause protein deposition and lens spoilage. Su et al. found that lipids in artificial tear solutions promote protein deposition on permeable contact lenses. These lenses are made from siloxanyl alkyl acrylate and fluorosiloxanyl alkyl acrylate, which form poly(SAA-FSAA). The lens matrix attracts hydrophobic lipid molecules while exposing hydrophilic regions to the aqueous en-

vironment. Lipids on lens matrices can reduce surface hydrophobicity, allowing proteins to bind and altering protein–lipid interactions [38].

#### 4.1.3 Methylcellulose–PEG hydrogels

Eyerich et al. found that methylcellulose–PEG hydrogels can reduce skin irritation [39]. They proposed using methylcellulose–PEG hydrogel for allergen delivery in skin tests because it may reduce skin irritation and abrasions.

### 4.2 Biosensing

Hydrogels are used in sensors to provide suitable hardness, elasticity, analyte diffusion, and refractive index. Smart hydrogels can concentrate diluted aqueous solutions of macromolecular solutes, such as proteins and enzymes, without affecting enzyme activity by changing temperature or pH according to molecular size and net charge [40]. Efficient hydrogels can reshape and shrink in response to environmental changes, making them suitable for purification devices. Immobilizing adsorbents in hydrogels, such as agarose and calcium alginate gel, helps reduce fouling caused by colloidal pollutants. Hydrogels can also regulate substrate interactions with immobilized enzymes by adjusting their swelling behavior [41].

Steroid conversion is higher in hydrophobic gels because of improved partitioning of water-insoluble steroids. Gholizadeh et al. reported that poly(2-oxazoline)-cholesteryl methyl carbonate is a suitable biomaterial for liposome modification in drug delivery. The hydrogel released a fluorescent tracer into the cytoplasm in response to reduced endosomal pH, as observed using confocal laser scanning microscopy. Doxorubicin hydrochloride-loaded PEtOz hydrogel showed higher antitumor activity at pH 6.4 than at pH 7.4 [42].

Liu et al. concluded that replacing pendant analyte groups in smart imprinted hydrogels reduces effective crosslinks, increases mesh size, and regulates release. When analyte concentration decreases, the protein binds to the pendant group and closes the network structure. Therefore, the hydrogel competes with the free analyte in solution for binding. Figure 1 shows that molecular binding at active sites can change hydrogel hydrophilicity or hydrophobicity, thereby altering swelling. Figure 1 illustrates the binding of analyte A to a covalently bound enzyme E. The cationic hydrogel is pH -sensitive and can ionize, swell, and release the active ingredient, peptide, or protein. Panel B represents the analyte at a specific concentration. When the analyte competes with the protein, it binds to the protein, leading to reversible loss of strong crosslinks and allowing release to occur. Panel C illustrates swelling caused by the analyte. Panel D represents analyte-binding groups randomly incorporated into the network during polymerization, demonstrating analyte binding to the drug, peptide, or protein while competing for binding sites.

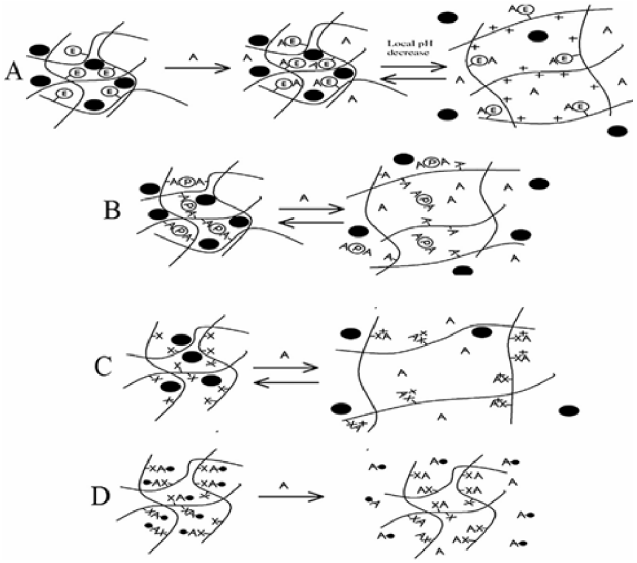


**Fig. 1** Smart analyte-sensitive hydrogels [43].

Hydrogels are widely used for targeted delivery to the stomach, liver, colon, intestine, brain, blood, nervous system, and tumors. Hydrogels are important in pharmaceutical applications because of their controlled drug-delivery ability. Adding PVA and increasing crosslinking can prolong the release period of composite PVA beads with a double-layered structure for controlled drug delivery. Khan et al. investigated composite PVA beads designed for controlled drug release and concluded that release duration could be prolonged by increasing PVA content and the degree of crosslinking [44].

Traitel et al. developed an insulin-release system under simulated physiological conditions using poly(2-hydroxyethyl methacrylate-co-N,N-dimethylaminoethyl methacrylate), also known as poly(HEMA-co-DMAEMA), containing glucose oxidase, catalase, and insulin [45]. When exposed to physiological fluids, glucose diffuses into the hydrogel and is converted into gluconic acid by glucose oxidase. This promotes swelling of the pH -sensitive hydrogel and insulin release. Hydrogels without chemical crosslinking were more stable in water

and showed greater swelling and glucose sensitivity than chemically crosslinked hydrogels, Figure 2.

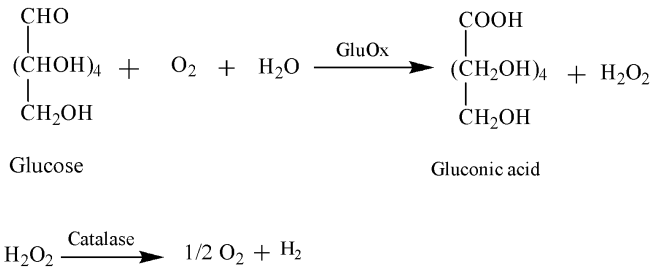


**Fig. 2** Enzymatic reaction of glucose oxidation and catalytic decomposition of hydrogen peroxide.

Temperature-responsive hydrogels, including polyacrylamide derivatives, are effective for pulsatile drug release because of their hydrophobic interactions and ability to shrink at specific temperatures. This enables control over drug delivery. Peng et al. developed a temperature-sensitive composite hydrogel for pharmaceutical applications using PNIPAAm-PEGDA. Both micro- and nanoparticles were successfully loaded with more than 80% of the incubated bovine serum albumin (BSA). The study showed temperature sensitivity and the advantage of in situ polymerization for selective localization [46, 47].

### 4.3 Anti-fouling and coating

The term biofouling describes surface contamination caused by the adhesion of organisms and their byproducts. Biofouling on implantable medical-device surfaces is caused by the adhesion of microorganisms or thrombotic components as part of a foreign-body reaction [48]. Biofouling affects the functional lifetime of implanted medical devices and may require device removal or replacement [49].

Biofouling is a complex process influenced by the physical and chemical properties of the target surface. Surface modification can improve the antibiofouling properties of implantable medical devices by regulating surface hydrophilicity, charge, biomolecule functionalization, and drug release [48]. On hydrophilic surfaces, resistance to foulingspecies adhesion is attributed to the formation of a hydration layer between the coating and the environment. This hydration layer acts as a physical barrier that prevents fouling species from adhering.

Hydrogels are hydrophilic materials that can significantly increase the hydrophilicity of coating surfaces. Commonly used hydrogels for antifouling coatings on implantable medical devices include polyvinyl alcohol (PVA), polyethylene glycol (PEG), and natural polysaccharides, such as chitosan and dextran [50, 51]. PEG is considered a goldstandard antifouling material. The positive charge of some polysaccharide hydrogel backbones can disrupt microbial lipid membranes and exert antimicrobial effects.

Another type of antibiofouling hydrogel coating consists of zwitterionic hydrogels. These hydrogels are electrically neutral and contain equal distributions of positive and negative charges within the polymer framework [3, 52]. Commonly studied zwitterionic materials are prepared by attaching polysulfobetaine or polycarboxybetaine to methacrylate or acrylamide structures. The hydration layer formed on the surface of zwitterionic hydrogel coatings is strongly bound to the coating surface through electrostatic interactions.

### 4.4 Agriculture and soil water management

The addition of hydrogel polymers can increase soil water-holding capacity by 50 – 70% when the soil-to-hydrogel ratio is properly adjusted. It can also reduce soil density by 8- 10%. Soil saturated water content increases with increasing hydrogel dosage, clearly demonstrating improved water-use efficiency in agriculture, especially in arid and semiarid regions. This positively affects crop yield. Hydrogels directly influence soil properties such as permeability, density, structure, texture, evaporation, and infiltration rates. They can reduce irrigation frequency, compaction problems, and runoff while increasing aeration and microbial activity [53].

Water stress caused by moisture deficiency in the root zone is often associated with early leaf drop, reduced chlorophyll levels, decreased seed production, and lower fruit and flower yields per plant, as shown in Figure 3. Hydrogel application can help reduce the effects of water deficiency. As water-retaining agents, hydrogels can significantly prolong irrigation intervals, thereby improving irrigation efficiency, particularly in arid and semi-arid regions [54].

### 4.5 Industrial and cosmetic applications

One of the primary roles of the skin is to protect the body from environmental factors, such as microbes and ultraviolet radiation. The skin also helps regulate body temperature and fluid balance [55]. Skin moisture is important for maintaining appearance and texture. Natural aging, genetic factors, sunlight exposure, environ-

mental conditions, and pollution can all contribute to skin damage, with sunlight being one of the main causes [56].

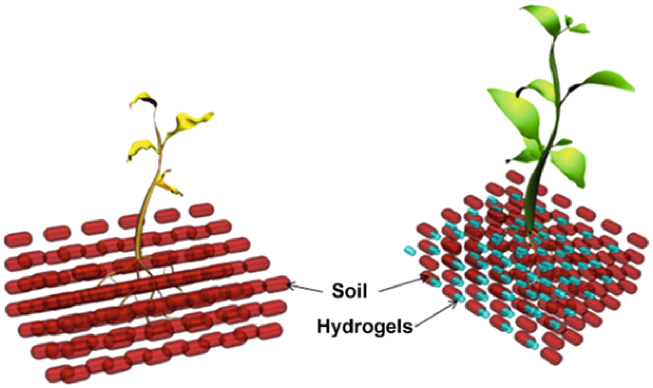


**Fig. 3** Mechanism of hydrogel action in agricultural soil: enhanced water retention leading to improved plant growth [57].

Cosmetics are used to improve the appearance and texture of the skin. Moisturizing creams, body lotions, and skin cleansers are among the cosmetic products used for body care. Currently, the cosmetics industry is focusing on hydrogels because of their biocompatibility, flexibility, softness, and high moisture-retention ability. Hydrogels can address various skin concerns, including cellulite, wrinkles, pigmentation, dehydration, and signs of aging. Bioadhesive hydrogels loaded with caffeine are mainly designed for cellulite treatment or gynecological cosmetic uses [24]. The bioadhesive properties of hydrogels help gradually release caffeine into the skin, improving skin appearance and texture. Hydrogels used in cosmetics can also support regeneration and restore skin softness, elasticity, and hydration. These hydrogels may contain hyaluronic acid and collagen. Hyaluronic acid is important for skin hydration because it helps retain moisture in the skin [58].

In addition, hydrogels can be used in contact lenses, which can correct vision, deliver medications for ocular disorders, and serve cosmetic purposes. Contact lenses are generally classified into rigid and soft types. Rigid contact lenses are made of polymethyl methacrylate (PMMA), which has surface wettability, a high elastic modulus, and excellent durability [59]. However, the lack of oxygen permeability can negatively affect the eyes. The first hydrogel-based contact lenses were made using poly(2-hydroxyethyl methacrylate) (PHEMA). Hydrophilic polymers, such as polyvinyl alcohol and polyacrylonitrile, have also been studied for producing hydrogel contact lenses [60]. Soft or hydrogel contact lenses must have high water content and allow both water and oxygen to pass through. Oxygen permeability in hydrogel lenses is closely related to water content and lens thickness [61].

### 4.6 Oil–water separation and environmental remediation

Pollution caused by oily wastewater poses a significant risk to marine and aquatic environments worldwide because of increasing industrial oily wastewater and frequent oil spills. Therefore, the need for effective, low-cost, and reusable oil-water separation materials is increasing. Because water and oil are immiscible, materials with very high affinity for either water or oil are promising candidates for oil-water separation [62].

Oil-removal materials are usually superhydrophobic or superoleophilic, allowing oil to pass through while water remains on the other side. Examples include polyester fabrics, carbon-based materials, hydrophobic aerogels, polystyrene, and polytetrafluoroethylene (PTFE)-coated fabrics. However, because of their oleophilic properties, these materials are easily clogged by oil within pores and fouled on the surface, leading to reduced separation performance and shorter service life [63].

Unlike oil-removal materials, water-removal materials exhibit underwater superhydrophilic and superoleophobic properties. Hydrogels are well-known hydrophilic materials with water content exceeding 95% by weight. However, when used alone as base materials for oil-water separation, hydrogels often show insufficient water flux, usually less than 30 L $m^{-2}$ $h^{-1}$ bar $^{-1}$, because their network size is in the range of approximately 10 nm [64]. Coating commercial filter membranes with hydrogels combines the high flux of filter membranes with the hydrophilicity of hydrogels [65].

Gao et al. used layer-by-layer self-assembly to deposit a thin alginate hydrogel film onto the surface of a poly(acrylic acid)-grafted polyvinylidene fluoride (PAA-g-PVDF) filter membrane using sodium alginate and $Cu^{2+}$. The hydrogel-encapsulated PAA-g-PVDF filter membrane exhibited a water flux of up to 1230 L $m^{-2}$ $h^{-1}$ bar $^{-1}$, separation efficiency exceeding 99.8%, and excellent recyclability [66]. Yuk et al. coated a microporous metal substrate, with mesh sizes of $34 - 380\mu$ m, using a rough nanostructured hydrogel instead of coating a conventional filter membrane surface [67]. This hydrogel-coated mesh selectively and efficiently removed water from various oil-water mixtures, including vegetable oil

and crude oil, with efficiency greater than 99%. These underwater superhydrophilic and superoleophobic hydrogel-coated membranes have advantages such as antifouling behavior and recyclability, making them attractive for treating oily industrial wastewater and remediating oil spills.

### 4.7 Actuators and soft robotics

Stimuli-responsive hydrogels used as active actuation materials undergo relatively large deformation when exposed to external stimuli such as pH variation, temperature fluctuation, magnetic fields, hydraulic pressure, or air pressure. Hydrogel responsiveness can be achieved by synthesizing hydrogels from stimuli-responsive polymer networks, such as poly(N-isopropylacrylamide) for thermal responsiveness and poly(acrylic acid) for pH responsiveness. It can also be achieved by incorporating active components into the hydrogel matrix, such as magnetic particles for magnetic-field responsiveness, or by designing structures with chambers or channels for actuation through hydraulic or pneumatic pressure [68].

Active hydrogel coatings are usually based on stimuli-responsive polymer networks. Upon stimulation, conformational changes or changes in crosslink density induce hydrogel swelling or shrinking, resulting in actuation. A bilayer structure is one of the most commonly used configurations for hydrogel-coating-based stimuli-responsive actuators [69]. This dual-layer system can include different hydrogel coatings that respond to stimuli, enabling reversible and bidirectional actuation. By using a bilayer structure as the core element, complex shape changes from two-dimensional to three-dimensional structures can be achieved through careful structural design or patterning of active hydrogel coatings [70]. Furthermore, temperature-responsive hydrogel coatings can regulate fluid flow in microfluidic devices by periodically expanding and contracting in response to temperature changes [71].

### 4.8 Conductive and iontronic hydrogels

Hydrogels can gain ionic conductivity through mobile ions generated by dissolving salts in their water content. The resistivity of saltwater gels can be reduced to approximately $10^{-1}\Omega \cdot$ m, compared with pure water, which has a resistivity of approximately $18.2\text{M}\Omega \cdot$ cm. Living organisms primarily use ions to transmit electrical signals, whereas machines generally depend on electrons. Recently, the field of hydrogel iontronics has developed rapidly [72].

### 4.9 Nanocomposite hydrogel

In recent years, the development and application of nanocomposite hydrogels have become increasingly important. The combination of hydrogels and nanofillers provides high biocompatibility, biodegradability, and improved physical properties, including electrical and thermal conductivity, magnetic behavior, optical properties, antibacterial activity, and biological functionality. These unique properties have led to their widespread use in biomedicine, environmental protection, the oil and gas industry, and the food industry.

Hydrogel composites have excellent properties, such as high swelling and deswelling ratios, non-toxicity, biocompatibility, and biodegradability. They are useful in agricultural and biomedical applications, including controlled drug and protein delivery, wound dressings, tissue engineering, pharmaceutical applications, antibacterial materials, biosensors, and personal health diagnostics. In environmental protection, highly absorbent hydrogels are used for removing pollutants, such as dyes and heavy metals, from industrial wastewater and for improving soil quality. In the oil and gas industry, they can be used to enhance oil recovery and control unwanted water production in oil wells. Nanocomposite hydrogels have also attracted attention in food science, especially for improving food quality, nutrition, texture, sensory properties, and responsive food packaging. However, their application in food science remains limited. Recent reviews have summarized developments in nanocomposite hydrogels for various applications and provided detailed information on hydrogel-based nanocomposites and nanoparticle types [73].

### 4.10 Heavy metal and pollutant adsorption

Hybrid hydrogels based on pectin and carboxymethyl cellulose were prepared using epichlorohydrin (EPH) as a crosslinking agent for heavy metal ion adsorption. The effect of crosslinking-agent content on hydrogel swelling behavior was investigated, and the highest swelling ratio was observed at 8%(v/v) EPH at room temperature. Several analyses, including FTIR, SEM, TGA, DSC, and AFM, were performed to evaluate the morphology and thermal stability of the hydrogels. Adsorption capacity at different metal-ion concentrations was determined using atomic absorption spectroscopy, and the adsorption data were analyzed using the Freundlich isotherm model. These hydrogels exhibited significant ability to adsorb Cu, Pb, and Ni ions [74].

A superabsorbent polymer gel prepared from lignocellulose and crosslinked with magnesium aluminum silicate (MOT) was developed to remove Zn (II) ions from water. Lignocellulose was prepared by ultrasonic treatment followed by intercalation with clay to obtain nano-LCE-MOT. Various characterization techniques were used, including nitrogen adsorption-desorption, FTIR, SEM, and energy-dispersive X-ray spectroscopy. Adsorption kinetics followed a pseudo-second-order model, and adsorption was analyzed using the Langmuir isotherm model. The gel showed a high maximum adsorption capacity of 513.48 mg/g. Optimal adsorption conditions and desorption methods were also reported [75].

### 4.11 Food packaging industry

Biopolymers are being developed by research groups and industrial companies worldwide to provide eco-friendly packaging solutions, including food packaging. Biopolymers derived from biomass, such as proteins, polysaccharides, and lipids; microorganisms, such as polyhydroxyalkanoates; and conventional chemical synthesis, such as polylactic acid, are all used to develop new food-packaging materials. However, biopolymers have lagged behind pharmaceutical materials because of their high cost, low strength, and poor water resistance. Until recently, these limitations were addressed by combining natural and synthetic polymers or adding organic additives [76].

Hydrogels can be used as alternatives for producing efficient and attractive biopolymer packaging materials. The properties of biopolymers are strongly influenced by their specific nature. When linear polysaccharides, such as pectin and xanthan gum, are mixed with proteins, they form complexes that can be used to produce gel sheets, membranes, and coatings. Acacia gum, which is a more flexible polysaccharide, forms spherical structures, such as microcapsules and nanocapsules, that can encapsulate active substances and be incorporated into films. Proteins with high molecular weight and flexibility are well suited for developing protein-polysaccharide combinations because they can withstand conformational changes during different associations, such as electrostatic interactions, hydrophobic interactions, and physical entanglements [77]. Different protein-polysaccharide mixtures have been proposed for food packaging, each with advantages and drawbacks. Hydrogels show great potential in food packaging by enhancing gas and moisture barriers, providing antibacterial properties, enabling monitoring of product conditions, incorporating nanoadditives, prolonging shelf life, preventing oxidation, and performing specific functions.

### 4.12 Enhanced oil recovery

High water production from long-term flooding in mature reservoirs can cause corrosion, scaling, environmental concerns, and early shut-in of hydrocarbon-producing wells. To reduce excess water production and increase hydrocarbon production, hydrogels can be injected near the wellbore to block high-permeability zones or fractures. This redirects injected water into low-permeability, unswept, hydrocarbon-rich zones [78].

Previous studies faced difficulty dispersing polymers in clay using magnetic stirring. In solution, electrostatic interactions between clay edges and surfaces form tactoids, or "house-of-cards" structures, preventing proper clay dispersion and polymer intercalation. To improve clay dispersion, chemical modifications were used to generate negative charges on both the clay surface and edges. High-shear mixing was used to separate clay platelets and create exfoliated nanostructures. This created temporary dispersion until the polymer was added and crosslinked, resulting in a three-dimensional gel network.

To understand the behavior and properties of nanocomposite gels, a mechanism involving polymer-clay interaction has been proposed. The model suggests that negatively charged polymer chains bind to positively charged clay edges, producing interactions at the polymer-clay interface. This interaction is further strengthened by hydrogen bonding between oxygen atoms in the clay and hydrogen atoms of the polymer amide side chains, together with interactions between metal ions on the clay surface and carboxylate groups of the polymer. The resulting nanocomposite gel demonstrates excellent mechanical properties, making it suitable for reducing excess water production through profile modification and as a water-shutoff agent in enhanced oil-recovery methods.

### 4.13 Specialized applications

A cellulose-based superabsorbent polymer composite, poly(acrylic acid-co-acrylamide-co-2-acrylamido-2-methyl-1-propanesulfonic acid) grafted onto nanocellulose and polyvinyl alcohol, P(AA-co-AAm-co-AMPS)-g-NC/PVA, was developed for amoxicillin delivery. The composite was prepared using a graft copolymerization technique. The material was characterized using FTIR, XRD, SEM, and DLS. Equilibrium swelling tests were performed to analyze responsiveness to different

stimuli and to measure drug encapsulation efficiency at different amoxicillin concentrations. Drug-release tests were conducted under simulated gastric and intestinal conditions and followed a non-Fickian release mechanism, particularly at pH 7.4 [79].

Bioabsorbent aerogels based on cellulose nanofibers (CNFs) were developed for use in infant diapers. These CNFs, prepared with different oxidation levels, were evaluated for free swelling capacity using the TEMPO method [80]. The results showed that CNFs exhibited higher free swelling ability than standard cellulose pulp and typical absorbent diapers. This suggests that these bioabsorbents may be suitable alternatives to conventional superabsorbent polymers used in diapers. The study highlighted the main advantages of CNFs, including biodegradability and sustainability [81, 82].

## 5 CONCLUSION

This review summarizes the literature on hydrogels from the past two decades and presents a comprehensive classification based on their physical and chemical properties. Hydrogels are important polymeric materials characterized by hydrophilic structures and the ability to retain large amounts of water within a three-dimensional network. The shift toward synthetic hydrogels has been noted in several applications because of their improved water retention, longer service life, and wider variety of chemical raw materials compared with natural hydrogels.

A major focus of current research is stimuli-responsive hydrogels, also known as smart hydrogels. These functional materials can mimic biological tissues and exhibit rapid, significant, and reversible volume changes in response to environmental changes, such as temperature, pH, ionic strength, and electric or magnetic fields. This versatility has led to wide applications in biomedicine, including drug delivery, wound dressings, and tissue engineering; environmental protection, including heavy metal adsorption and oil-water separation; and industrial fields, including actuators and cosmetics.

Furthermore, superabsorbent polymers and superabsorbent hydrogels are recognized as environmentally friendly materials with a remarkable ability to rapidly expand and absorb large volumes of aqueous fluids. Despite major progress, several challenges must be addressed to fully realize the potential of hydrogel technology. These include interfacial adhesion limitations, application-specific material requirements, low fluid flow in separation materials, limited use in emerging fields, and sensitivity during preparation. Hydrogel preparation requires careful control because the design and preparation conditions strongly influence the final physical and chemical properties.

Future research should focus on reducing structural complexity while maximizing functional performance, particularly through advanced structural engineering and material hybridization. In addition, hydrogels should be developed with greater robustness, deeper penetration ability, and improved biodegradability for applications such as bone scaffolds, tissue engineering, and agricultural water management.

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