

## Review Article

# Poly(vinyl alcohol) Hydrogels: The Old and New Functional Materials

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Hydrogels have three-dimensional network structures, high water content, good flexibility, biocompatibility, and stimulation response, which have provided a unique role in many fields such as industry, agriculture, and medical treatment. Poly(vinyl alcohol) PVA hydrogel is one of the oldest composite hydrogels. It has been extensively explored due to its chemical stability, nontoxic, good biocompatibility, biological aging resistance, high water-absorbing capacity, and easy processing. PVA-based hydrogels have been widely investigated in drug carriers, articular cartilage, wound dressings, tissue engineering, and other intelligent materials, such as self-healing and shape-memory materials, supercapacitors, sensors, and other fields. In this paper, the discovery, development, preparation, modification methods, and applications of PVA functionalized hydrogels are reviewed, and their potential applications and future research trends are also prospected.

## 1. Introduction

Polymer hydrogel networks are low crosslinking materials, which can be formed by chemical or physical crosslinking methods and form covalent or noncovalent crosslinking points. Such networks can expand or contract, absorbing and retaining large amounts of water while insoluble in water [1, 2]. Hydrogels can usually be molded into certain shapes under natural conditions and exhibit good flexibility under certain pressure. Such kind of functional polymer

materials with water absorption, water retention, controlled release, and other functionalized properties have received huge research interests that developed rapidly in recent years.

Design strategies of functional hydrogels have been extensively studied. Hydrogels prepared *via* various chemical and physical interactions often showed excellent characteristics, such as stimulus responsive, biocompatible, reversible physicochemical, and other properties [3]. Hydrogels have similarities with human soft tissues in composition, structure,

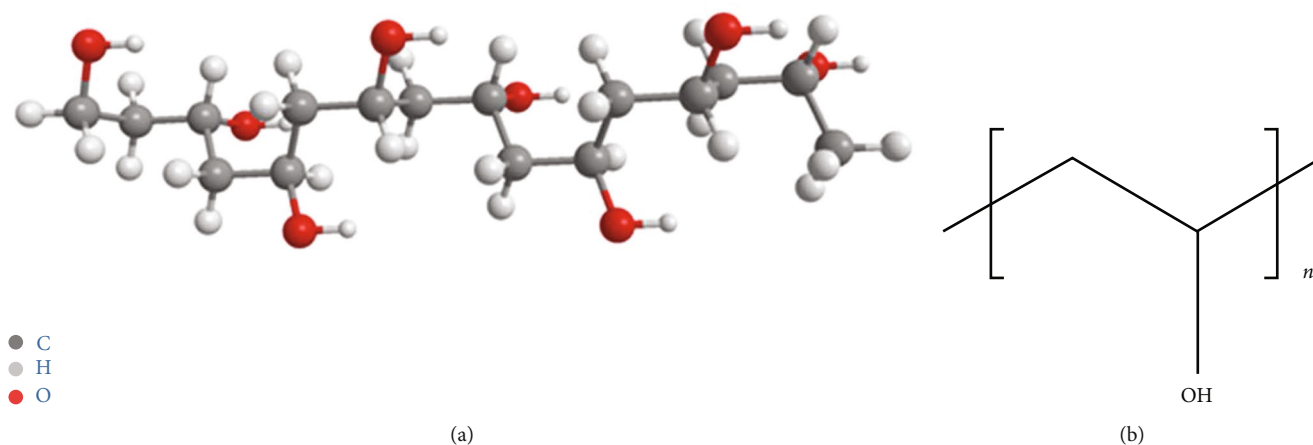


FIGURE 1: Molecular sketch (a) and chemical structure (b) of PVA chain.

and properties. Therefore, they are widely used in drug delivery, cell culture, tissue engineering, and other biomedical and biomimetic applications [4]. Besides, functionalized hydrogels have broad application prospects in many aspects, such as intelligent sensing and environmental treatment [5].

As one of the old polymer hydrogel materials, poly(vinyl alcohol) (PVA) has shown new vitality in recent years. Many studies have shown that it has the value of the further study. PVA (Figure 1) is a water-soluble long-chain polymer obtained by alcoholysis, hydrolysis, or ammonolysis of poly(vinyl acetate) (PVAc). PVA-based hydrogels are colloidal dispersion with three-dimensional network structures through crosslinking and swelling. They have attracted much attention due to their low toxicity, high water absorption, good mechanical properties (i.e., high elastic modulus and high mechanical strength), and good biocompatibility [6, 7]. Much attention also focused on their applications in the food industry, forestry, and super absorbent, especially in biomedicine, such as drug delivery carriers, tissue engineering scaffolds, implanted artificial muscles and organs, biosensors, wound dressings, and soft robotics.

In this review, we summarized the preparation, modification, and applications of PVA hydrogels, especially focused on the frontier works, and a prospect of future development was given at last.

## 2. Development, Preparation, and Modification Methods of PVA Hydrogels

**2.1. Discovery and Development of PVA Hydrogels.** In the early 1970s, frozen gelled PVA was proposed for biomedical applications [8]. In the same period, Peppas pioneered a series of studies on preparation techniques of PVA hydrogels. By measuring the turbidity of PVA samples crystallizing in the gelation process, the crosslinking reaction of PVA in the crystallization process was deeply understood, and the relationship between crystallization, PVA concentration, and gelation time was studied, thus, expanding the application of PVA hydrogels in sensing, biomedical, and other aspects [9–12]. Since then, more and more efforts have been devoted to researching formation, modification, char-

acterization, and applications of PVA hydrogels. After decades of exploration, thanks to the progress of research technology (e.g., 3D printing), the applications of PVA hydrogels as advanced functional materials have been extensively expanded, such as 3D-printing tissue engineering material [13, 14], self-healing gels [15], shape-memory materials [16], wearable electronic skin, and colorimetric sensors, showing that this material has more potentials and possibilities.

**2.2. Preparation and Modification of PVA.** At room temperature, a solution of highly alcoholysis PVA (>98%) can autonomously and slightly gelated between molecular chains into hydrogels. However, such hydrogel has poor mechanical properties and applications due to the low gelation density [17, 18]. In order to prepare PVA hydrogels with high mechanical strength, high water content, and good transparency, the ideal polymer network structure should be obtained through different crosslinking methods and preparation conditions. According to the crosslinking mechanism of polymers, the preparation of PVA hydrogels can be divided into physical crosslinking, chemical crosslinking, and radiation crosslinking.

**2.2.1. Physically Crosslinked PVA Gels.** At present, the repeated “freezing-thawing method” is the most commonly used physical crosslinking process [19, 20]. The physical and mechanical properties of the hydrogels, so-called cryogels, obtained by physical crosslinking could be greatly improved, and the crosslinking process is thermally reversible. Gelation properties can be improved by changing the type of solvent or by using a mixture of dimethyl sulfoxide (DMSO) and water [21].

The gelation mechanism (c.f. Figure 2(a)) of this physical method includes (1) the polymer chain aggregation region and nonaggregation region are formed at the initial stage of gelation, resulting in an network structure due to the function of intramolecular hydrogen bond; (2) when PVA solution was frozen, the movement of molecular chains was weakened, and the contact time between chains became longer while the distance between chains was shortened,

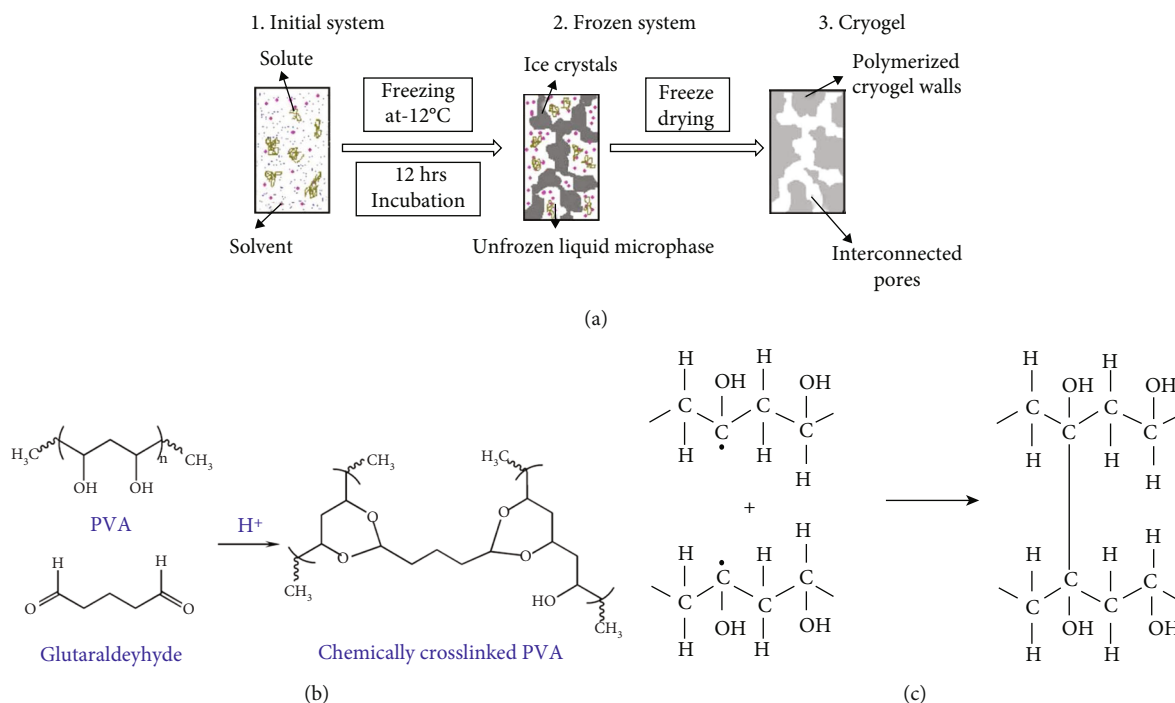


FIGURE 2: Gelation schemes of PVA are formed by: (a) physically crosslinking (freezing-thawing) [19], (b) chemically crosslinking (an example of glutaraldehyde as crosslinker), and (c) radiation [30].

which promoted the formation of hydrogen bond association between hydroxyl groups both inter/intramolecular [22, 23]. The PVA hydrogels prepared by the freezing-thawing method do not use toxic organic crosslinker that maintains good biocompatibility. With the change of environmental parameters (such as temperature, pH value, and osmotic pressure), the properties of the physical crosslinking points can be changed, and the sol-gel states are reversible. Thus, the physical PVA gels still have great potential in many fields.

**2.2.2. Chemically Crosslinked PVA Gels.** Chemical crosslinking is the most commonly used preparation method of hydrogels, and the hydrogel properties are affected by the concentration of monomer, crosslinker, and reaction conditions. For PVA, chemical crosslinkers could form chemical crosslinking points between PVA molecules to form gels (Figure 2(b)). Commonly used crosslinkers include epichlorohydrin, boric acid, aldehydes, and heavy metal compounds that form complexes with PVA molecules [24–27]. The chemically crosslinking reaction is rapid, but nonuniform crosslinking structures often occur due to the inhomogeneous dispersion of the crosslinkers. Although there are some biocompatible crosslinkers, for example, multicarboxylic acids, as an environmentally friendly solvent, are used as a crosslinking agent for chitosan/PVA nanofibers, which can increase the cellular compatibility of the fibers [28]. However, at present, most of the chemical crosslinkers are usually biotoxic and hard to remove, which have huge damage to tissue cells and cause inflammation after implantation, and hardly reduces the biocompatibility of the hydrogel materials [29].

**2.2.3. PVA Gels Crosslinked by Radiation.** Radiation crosslinking utilizes high-energy rays, such as gamma-ray, electron beams, and X-ray, that directly radiate PVA solutions. As shown in Figure 2(c), when PVA is irradiated at high energy, it can generate macromolecular free radicals (P·), mainly from the direct action of irradiation and the action of water radiolysis active particles (S·). The free radicals generated by the irradiated PVA can be located on secondary and tertiary carbons, respectively. Two macromolecular free radicals are crosslinked together through the double-group coupling reaction to produce crosslinking bonds. With the increase of crosslinking bonds, they begin to gel and gradually form a three-dimensional network structure throughout the whole system [31–33]. The PVA hydrogels produced by radiation are free of crosslinkers and therefore have high purity and good optical transparency. At the same time, high-energy reaction conditions often cause the loss of mechanical properties and other aspects. Another advantage of PVA hydrogels prepared by radiation crosslinking is that the reaction is rapid and can be achieved at room temperature and atmospheric pressure [30, 34]. However, due to radiation intensity, many materials cannot be added to the hydrogel systems.

### 2.3. Modification of PVA Hydrogels

**2.3.1. Chemical Modification.** Neat PVA hydrogels are not sensitive to environmental stimuli. Thus, functional monomers/polymers are used to prepare hybrid hydrogels with modified properties [35]. The molecular structure of PVA could commonly be modified by grafting functional groups onto PVA backbones. For instance, the PVA containing

carboxyl side group can be obtained by esterifying PVA with phthalic anhydride or succinic anhydride [36]. A charged group-modified PVA hydrogel was reported on the basis of copolymerization crosslinking of acylated PVA with [2-(methacryloyloxy) ethyl] trimethyl ammonium chloride (DMC) monomers, such hydrogel possessed a macroporous structure, high porosity, appropriate swelling ability, and mechanical property. It exhibited excellent stability over a broad pH range [37]. PVA can also react with bifunctional compounds such as aromatic diglycidyl ether to obtain crosslinked PVA with a stereoscopic network structure, which improves the chemical stability and selectivity of PVA hydrogels [30]. As shown in Figure 3(a), PVA-based hydrogels such as 4-carboxybenzaldehyde (CBA)-PVA [38] and 2,3-dialdehyde cellulose (DAC)-PVA [39] have also been reported.

**2.3.2. Physical Modification.** By utilizing the intermolecular force between polymer chains to form molecular aggregates, the composite system with excellent properties could be achieved. Physical crosslinking chitosan (CS)/PVA blend hydrogels with only PVA gelated networks have been widely used in many fields [40, 41]. A 3D-printing hydrogel was developed by cooperating the physically gelated PVA as the stretchable polymer network together with alkaline polysaccharide CS, as shown in Figure 3(b), which improved the mechanical strength of such blend system [42]. Solvents including DMSO, ethylene glycol, and glycerol could serve as plasticizers that promote structural stability and help produce firmer PVA hydrogels due to the penetration of the PVA gel matrix [43–45]. A high-concentration solution of alkaline metal hydroxide can also promote the physical crosslinking of PVA, increase the crystallinity, and form elastic hydrogels with low water content and the swelling ratio [46, 47]. Besides, dual physical gels such as poly(ethylene glycol) (PEG)/PVA by one-pot method [48, 49] and poly(acrylamide-co-acrylic acid) (PAM-co-PAA)/PVA [4] by two-step method were also reported.

**2.3.3. Filler Reinforcement.** Composite with inorganic fillers or organic small molecules can also enhance the PVA hydrogels [34, 50]. Such kind of blending not only keeps the biological activity but also improves the mechanical properties (e.g., friction properties) of the PVA hydrogels [51–53]. At the same time, fillers have the advantage of increasing the content of borax to improve the mechanical strength of hydrogels, but also have the disadvantage of destroying the structure of hydrogels. Filling can promote the crosslinking degree of the gel, thus, reducing the water content and swelling rate of the gel, resulting in the shrinkage of the pores in the hydrogel [54]. Defects in the filler may affect the application of the gel. It has been reported that the addition of tricalcium phosphate nanoparticles increases the mechanical strength while decreases the swelling and degradation rate, pore size, permeability, and quercetin release rate of the hydrogel [55]. For instance, as shown in Figure 3(c), a series of hybrid graphene oxide (GO)/PVA composite hydrogels have been reported with different potential applications in artificial cartilage and tissue engineering [56, 57]. Besides,

Figure 3(d) shows a CS/PVA/CeO<sub>2</sub> hydrogel system that combined polymer modification and filler functionalization, which can be utilized as a wound-healing material [58].

### 3. Applications of Functionalized PVA Hydrogels

Biomedical polymer materials should have a series of characteristics such as nontoxic, good biocompatibility, degradability, and processability. The excellent properties of PVA hydrogel meet the requirements of biomedical polymers. Therefore, PVA has been widely used in drug delivery carriers [59, 60] and microcapsules [61], wound dressings [62], artificial organs and tissues [63], intelligent materials, and other fields.

**3.1. Drug Delivery Carriers and Microcapsules.** PVA hydrogels are used as drug carriers while small drug molecules are embedded, and the stability of the drug can be increased [59]. With the swelling of the hydrogels due to the Donnan potential, the releasing time of drugs can be greatly prolonged while the dosage of the drug can be reduced [63, 64]. Since PVA is stable to environmental stimulus, the releasing mechanism of drugs from PVA gels is proved and calculated as zero-order releasing mode [39, 62, 65, 66]. As can be seen in Figure 4(a), PEG/PVA hydrogel system could perform stable releasing of aspirin under different pH buffer solutions [50]. Such materials are investigated for certain cancer treatment and localized delivery [59, 66, 67]. Diabetes is a metabolic disease characterized by glucose, protein, fat, and other metabolic disorders that occur due to hypofunction of islets and insufficient insulin secretion [68], and glycerol adjusted PVA hydrogel with a long-acting effect was reported for the released of insulin [69]. The PVA/PEG system also showed good physical and chemical properties in pH-dependent drug delivery [36, 41] and wound healing [58, 70].

**3.2. Wound Dressing.** Although the traditional gauze dressings have a wide range of uses, there are many disadvantages in their application due to their small amount of absorption of excess wound exudate, frequent replacement, and adhesion with the wound [71]. Developing a nontoxic, super-absorbent, and antibacterial hydrogel as a skin wound dressing is of significant importance. As a wound dressing, PVA hydrogels can protect the wound and reduce the second injuries of external environment stimulus and external mechanical force applied to the wound, which is convenient for clinical operation (Figure 4(c)) [39]. Moreover, PVA hydrogels also have good permeability to water and oxygen and high moisture content that can maintain the moist environment of a wound during wound healing, promote the growth of new tissue, and promote wound healing [59, 72].

However, the PVA hydrogels themselves do not have antibacterial properties; in order, it is necessary to enhance the antibacterial performance of PVA hydrogels as dressing materials. Antibacterial modification mainly includes inorganic, organic, and natural antibacterial molecules. Silver nanoparticles are commonly used inorganic antibacterial



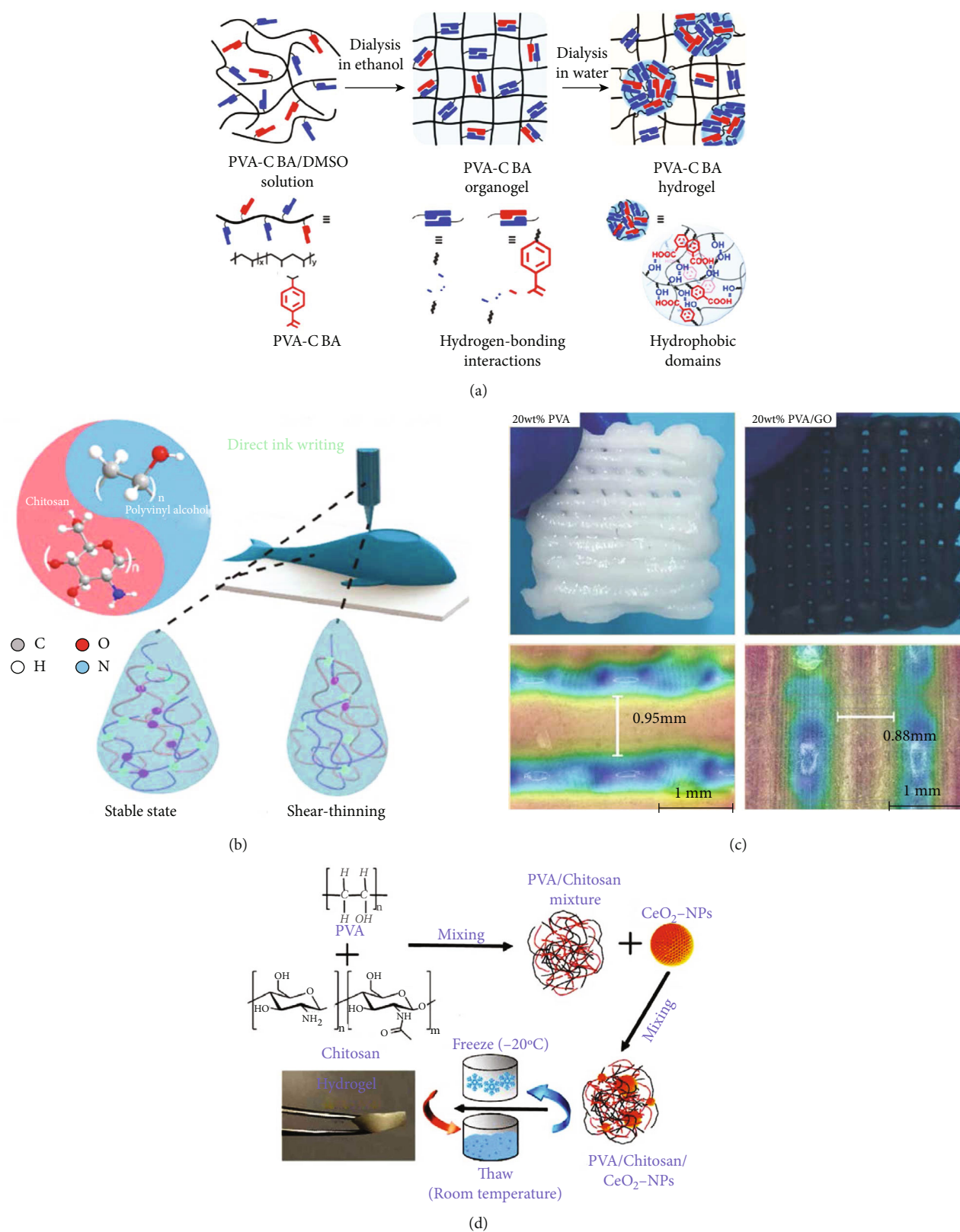


FIGURE 3: Modification of PVA by: (a) CBA-PVA (chemically) [38], (b) CS/PVA (physically) [42], (c) GO/PVA (filler) [57], and (d) CS/PVA/CeO<sub>2</sub> (polymer and filler) [58].

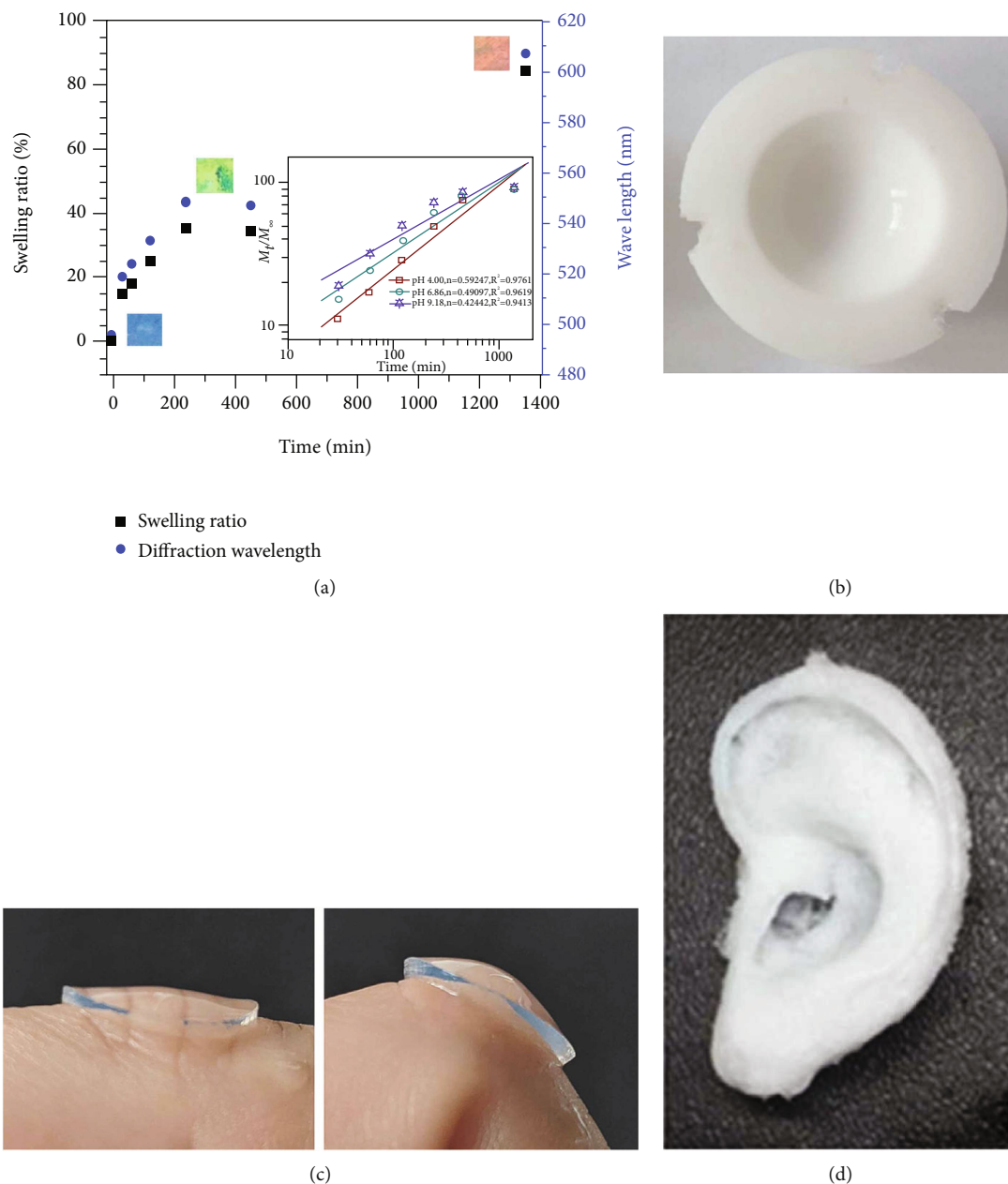


FIGURE 4: The biomedical applications: (a) controlled drug releasing from PVA/PEG hydrogels [48], (b) artificial acetabulum fabricated by PVA hydrogel [90], (c) bioadhesive wound dressing PVA hydrogel [39], and (d) PVA hydrogel-based ear-shaped artificial auricular cartilage [86].

agents, which are considered efficient and broad-spectrum antibacterial, but the main barrier for industry application is the high cost [73]. As mentioned above, the main strategies of organic modification for bio-oriented PVA hydrogels include filler reinforcement and chemical modification [50]. An in situ formed PVA-based hydrogel wound dressing that triggered by glucose in wound exudate due to the existence of glucose oxidase in gel solution was reported [74]. Natural antibacterial molecules, such as CS, are green and environmentally friendly materials. In the PVA/CS system, the addition of CS can not only improve the thermal stability and mechanical properties of PVA hydrogels but also adjust the water content of PVA hydrogels [40, 58, 75–79].

The antibacterial materials of the PVA hydrogel systems are generally expensive, and the modification methods are complicated. Therefore, the preparation of antibacterial PVA hydrogels with low cost and simple preparation, large-scaled production method is the research focus [80].

**3.3. Tissue Engineering.** Scaffold material plays an important role in tissue engineering. An ideal scaffold material should have the following characteristics: nonimmunogenicity, nontoxicity, good biocompatibility, high porosity, degradability, appropriate degradation rate, and easy manufacturing [81]. With the development of cartilage tissue

engineering, the composite of hydrogel/cells is one of the main materials for cartilage regeneration [82]. Hydrogels have many similarities with articular cartilage and therefore are ideal substitutes for articular cartilage [83]. As a spatial framework for cell proliferation and differentiation, hydrogels can be beneficial to cell transplantation, which also allow free entry of nutrients and oxygen and provide transport conditions for the secretion of cells.

Hydrogel elastomers have similar tribological properties and physical properties such as high water content as articular cartilage [57, 84], which may serve as a substitute for articular cartilage to repair articular cartilage defects, restore the integrity of the articular surface, and maintain joint function, and their potential advantages are (1) many synthetic polymer gels have shown good biocompatibility [81]; (2) similar to natural cartilage, in addition to the basic structure of solid-liquid phase, they also show expansion, viscoelasticity, and considerable compression stiffness and can withstand a certain load cycle; (3) after modification, the natural lubrication mechanism in cartilage tissue can be simulated [82–88]. Currently, hydrogels have been used to repair articular cartilage in two ways: (1) permanent implants replacement of damaged cartilage tissue and (2) being injected as cell carrier materials to stimulate tissue regeneration. Figure 4(d) showed an ear-shaped artificial auricular cartilage, which proposed that PVA hydrogel-based hydrogels might have found their applications as artificial organs [86]. As a kind of cell-free implant, hydrogels can be structurally and mechanically similar to cartilage and suffer effective load [89].

PVA hydrogels materials are potential candidates for artificial joints, artificial muscles, artificial vitreous body, artificial cornea, and iris. PVA hydrogel has porous, permeable structures that are similar to natural cartilage and contain much water. Liquid can be infiltrated and extruded under a certain load, which can be entrained as a lubricant. Hydrogels' high water content and surface structure are very similar to natural cartilage fabrics [52]; Figure 4(b) shows an artificial acetabulum fabricated by PVA hydrogel, which could suffer harsh friction test [90]. Under the condition of hyaluronic acid (HA) lubrication, PVA and human articular cartilage have similar tribological properties [59, 81]. However, like most synthetic polymer materials, PVA is non-toxic. However, it is a biologically inert polymer, which has a weak ability to adsorb proteins and cannot adhere to cells to form binding with living tissue. As a kind of natural polymer material, gelatin, a degradation product of collagen, has a protein chain similar to collagen and maintains a large number of amino ( $-\text{NH}_2$ ) and carboxyl ( $-\text{COOH}$ ) groups [91–93]. Therefore, through the composite modification of PVA hydrogel, the introduction of charged groups into the hydrogel composition can enhance its cell affinity and facilitate cell adhesion [94].

**3.4. Intelligent Materials.** Intelligent hydrogels can respond promptly to subtle changes or stimuli in the environment, such as temperature, pH value, electric field, and pressure. For instance, the thermosensitive hydrogel can shift its swelling degree according to the temperature of the environ-

ment to control drug release at desirable conditions. In recent years, more attention has been paid to self-healable, shape memory, and stimulus responsive materials, which can be made from PVA hydrogels and be implemented in intelligent devices. However, the structures and functionality of hydrogels can be damaged by external mechanical or chemical erosion, especially under complex internal environment conditions. Therefore, designing and synthesizing hydrogels with self-healing/shape memory ability is widely concerned by researchers.

**3.4.1. Self-Healing and Shape Memory Materials.** Unlike traditional hydrogels, self-healing hydrogel forms a spatial network through dynamic connectivity. Recently, self-healing hydrogels have attracted extensive research interest and have been applied to constructing various new intelligent materials [96]. Injection of self-healing hydrogels can deliver drugs *in vivo* without significant damage to the body since the hydrogels are embedded without surgical incision [97]. Therefore, compared with traditional hydrogels, self-healing hydrogels show great potential in various fields, such as self-healing, *in vivo* drug delivery, and sensors. The self-healing process and its results are mainly manifested in two aspects: (1) the recovery of micro/macrostructure (micro/macro morphology) and (2) the recovery of mechanical and rheological properties [38]. The strategies for synthesizing self-healing hydrogels are also including noncovalent (physical crosslinking) such as hydrophilic and hydrophobic bonds, hydrogen bonds, host-guest interactions, ionic bonds [98–102], and dynamic covalent bonds (chemical crosslinking) such as Schiff base linkages and disulfide linkages [103, 104].

PVA contains large amounts of hydroxyl groups that can form intermolecular hydrogen bonds *via* freezing-thawing methods and form a self-healing hydrogel network [15, 38, 95]. Figure 5(a) showed that PVA hydrogels with high polymer content could exhibit self-healing properties [17]. With the functionalization of other materials such as quantum dots, crystal array, and polymers, the healable PVA gels could reveal interesting applications. The dual physically crosslinked hydrogel was reported that formed by firstly entanglement between PAM-*co*-PAA and then cooperated with PVA by freezing/thawing process [4]. Such hydrogel showed not only good mechanical properties ( $1230 \pm 90$  kPa in strength,  $364 \pm 38$  kPa in modulus, and  $1250 \pm 50$  kJ/m<sup>3</sup> in toughness) but also rapid self-healing ability due to the hydrogen bond between PVA molecules and the PAA segment. In addition, the self-healing ability can be chemically enhanced due to the weak hydrogen bond effect. A series of PVA-based double/triple network hydrogels containing hydrogen bonding and metal ion coordination were reported [105–107]. Based on the synergistic effect of hydrogen bond and metal ion coordination, the hydrogel showed excellent self-healing efficiency. The self-healing properties of typical materials mentioned can be compared in Table 1.

In addition, the physically crosslinked PVA was introduced into the chemically crosslinked PEG network to form a double crosslinking network, such PEG/PVA hydrogel not only showed self-healing property but also available of shape

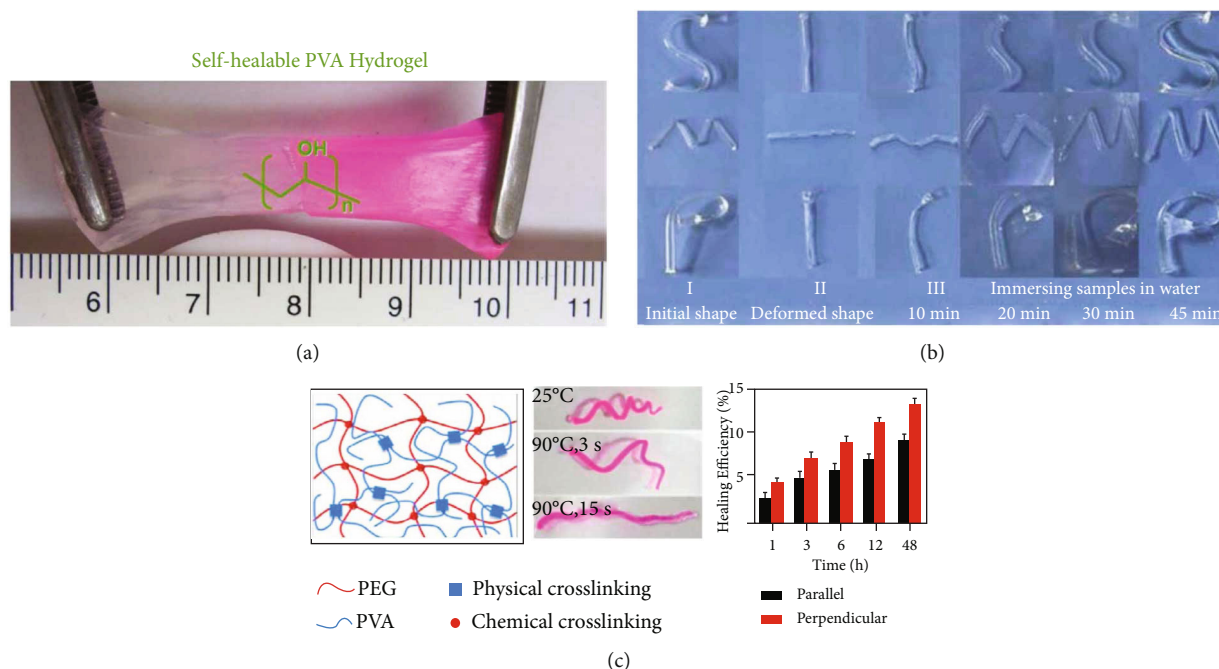


FIGURE 5: Schemes of PVA showing: (a) self-healing [15], (b) solvent-induced shape memory [16], and (c) temperature-induced shape memory behaviors [95].

TABLE 1: Self-healing properties of some reported PVA materials.

Synthetic strategy	Mechanical property	Healing time	Healing efficiency	Ref.
Hydrogen bond	Fracture stress $\sim 105$ kPa	10 s to 48 h	Up to 70%	15
Synergistic crosslinking of bimetallic ions	Tensile strain $\approx 1.011$ mm/mm, tensile stress $\approx 0.34$ MPa, elongation at break $\approx 74\%$	$<60$ s	Up to 95%	98
Hydrogen bond	Compression modulus is 39.6 kPa $\sim$ 74.0 kPa, maximum stress $\approx 29.0$ kPa	$\geq 4.68$ min	63.21%	101
Reversible hydrogen bond	Storage modulus $\approx 11.38$ kPa, loss modulus $\approx 4.036$ kPa	$\sim 10$ min	/	102
Hydrogen bond	Tensile stress $\approx 60$ kPa	$<24$ h	$\sim 74\%$	134

memory [95]. Shape memory hydrogels are reactive hydrogels that respond to shape change stimuli, which can deform and fix a deformed shape and can return to the original shape when stimulated by external forces [5]. The stimulus involves thermal, ion, pH, solvent, etc. Fully hydrated gels can be penetrated by small molecules that can trigger shape memory behavior. In general, chemically excited shape memory hydrogels have the dual properties of reversible and dynamic, which is helpful for the shape fixation and recovery of hydrogels. Reversible interactions like ammonia bond, host-guest interaction, and metal coordination interaction are used to realize the shape memory performance of hydrogels [16, 47]. Figures 5(b) and 5(c) show shape memory properties of different PVA hydrogels induced by solvent and temperature, respectively [16, 95].

**3.4.2. Supercapacitor.** An early electrochemical supercapacitor was assembled with glutaraldehyde crosslinked PVA hydrogel as electrolyte and activated carbon fiber cloth as

electrode [108]. Compared with electrochemical capacitors using 1 mol/L  $H_2SO_4$  aqueous solution as an electrolyte, the results showed that the ionic conductivity of the PVA hydrogel electrolyte was similar to that of the 1 mol/L  $H_2SO_4$  aqueous solution, and the PVA hydrogel assembled electrochemical capacitors showed a lower self-discharge effect. With the modification of PVA hydrogel, such as PAM/PVA, the specific capacitance can reach 230 F/g while the capacitance retention rate can be maintained at 98% after 5000 cycles [109]. Recently, acrylamide (AA) monomer was introduced into PVA/ $H_2SO_4$  solution to form a dual-crosslinked hydrogel electrolyte as all-in-one flexible supercapacitors whose energy density and power density reach up to  $14.2 \mu Wh/cm^2$  and  $0.94 mW/cm^2$ , respectively [110]. This supercapacitor also exhibited good mechanical strength that can suffer compressive stress of 0.53 MPa and be stretched up to 500%. Other recently reported PVA-based hydrogels also show excellent properties including high stability, capacitance, current density, and repeatability [46, 111–113].



TABLE 2: The properties of typical PVA-based hydrogel sensors.

Sensing target	Response time	Mechanical property	Characteristic	Ref.
Temperature	~1 s	Good elastic and mechanical properties	Moisture retention under normal temperature and moderate conditions (water retention 37% ~ 95%)	[44]
Strain	0.32 s	High tensile strain up to 500%, mechanical strength $\approx$ 900 kPa	Conductivity $\approx$ 1.85 S m <sup>-1</sup>	[116]
Strain	170 ms	Tensile strength $\approx$ 1360 kPa, elastic modulus $\approx$ 110 kPa	Low detection strain (0.25%), wide sensing range (0.8 kPa ~ 50 kPa), durable operation	[120]
pH and Pb <sup>+2</sup>	/	/	Capable of dehydration and rehydration	[123]
Glucose concentration	180 s	/	Low detection limit (glucose concentration: 0 ~ 20 mM)	[124]

**3.4.3. Conductive and Antifreeze Materials.** As functional materials, thermotolerance is also a very important characteristic. Similar to self-healing, acid/alkali resistance, antifreeze, and compression resistance can bring more possibilities for intelligent materials. As functional devices, frozen resistance property is also very important [110]. An antifreezing conductive hydrogel was reported, which was prepared by combining PVA with poly(3,4-ethylenedioxythiophene) and polystyrene sulfonate (PEDOT: PSS) with the assistance of ethylene glycol [114]. The hybrid hydrogel showed excellent strain-sensitive and conductive performance even at a low temperature of  $-40^{\circ}\text{C}$ . Recently, PVA/cellulose nanofibril (CNF) composite hydrogels were reported with freezing tolerant and conductive properties [115]. The hydrogels are obtained through freezing-thawing treatment with DMSO/water as an antifreeze solvent system. The introduction of CNF increased the mechanical properties and ionic conductivity of the composite hydrogels, resulting in tough products with 2.1 MPa in tensile strength and can be stretched up to 660%. The ionic conductivity maintained 1.1 S/m even at  $-70^{\circ}\text{C}$ . Similarly, antifreeze solvents such as diols and triols can be used to improve the properties of PVA hydrogels [43, 44]. However, the conductivity and mechanical properties of hydrogels and their application in ultrasensitive hydrogel electronic devices might be affected due to the introduction of solvents. In addition, biotoxic organic solvent-assisted hydrogels limit the practical applications in contact hydrogel devices, such as bionic electronic skin and bio-oriented sensors.

**3.4.4. Sensors.** Based on excellent physical and chemical properties, other functions such as antifreeze, self-healing, and stimuli response of PVA-based hydrogels can also be applied to act as specific sensing applications. The hydrogels respond to changes in the external environment, causing a swelling/shrinkage behavior. The change of the environment can be speculated by measuring the volume change of the hydrogels.

A PVA hydrogel-based temperature sensor with frost resistance, water retention, and moldability was prepared by introducing glycerol and silver nanofibers (AgNWs) into PVA hydrogel [44]. The hydrogel can be remolded due to the reversible physical crosslinking through freezing-thawing treatment. As a sensor, the hydrogel showed the good moisturizing properties. It can linearly change its

conductivity according to the temperature change in the range from  $5^{\circ}\text{C}$  to  $55^{\circ}\text{C}$  with a short response time and good repeatability. Interestingly, a similar PVA/AgNWs hydrogel sensor with biocompatibility and high stretchability was reported that can be applied as strain sensors. The hydrogel material can be stretched up to 500% while maintaining its sensing linearity, which can be applied to human skin and monitor the body motion [116]. Previous studies also showed that the introduction of PVA hydrogels in ion-conducting cellulose hydrogels increases the tensile properties of the sensors [117, 118]. In addition, this type of PVA-based hydrogel pressure sensor also has the characteristics of good sensitivity, high transparency, fast response time, and high reliability, demonstrating the great potential of wearable devices [119, 120].

Another sensing mechanism utilizes the so-called photonic crystals as colorimetric elements [121]. The long-term ordered colloidal crystal was embedded inside hydrogel; the crystal can diffract a certain frequency of visible light while the diffraction wavelength can be tuned by the lattice distance of the crystal [122]. Thus, as the hydrogel exhibit volume changes due to the environmental stimuli, the embedded crystal changes its lattice constant and shifts the diffraction color of the hydrogel system. Based on this mechanism, modified PVA hydrogels can be applied as a series of colorimetric sensors, including heavy metal [123], glucose [124], pH [41], and strain [43]. For instance, a glucose-sensitive photonic crystal material was reported, coated by a 4-boronobenzaldehyde-functionalized PVA hydrogel. During the glucose detection, glucose binds to borate and shrinks the hydrogel, and thus causing diffraction color of the hydrogel blue shift. As a result, 0.1–0.6 mM of glucose was distinguished by the color change of the sensor gel. The performances of typical PVA-based hydrogel sensors were listed in Table 2.

The long-term stability and sensitivity of flexible sensors designed with injectable, antifreeze, and intelligent sensing hydrogels as electrolytes at low temperatures remain urgent challenges. In addition, compared with traditional electronic materials, the disadvantages of hydrogels include low modulus and high water percentage, which may lead to poor integration of hydrogels and devices. Therefore, optimizing and improving the integration process of hydrogel-based sensors are urgent challenges.

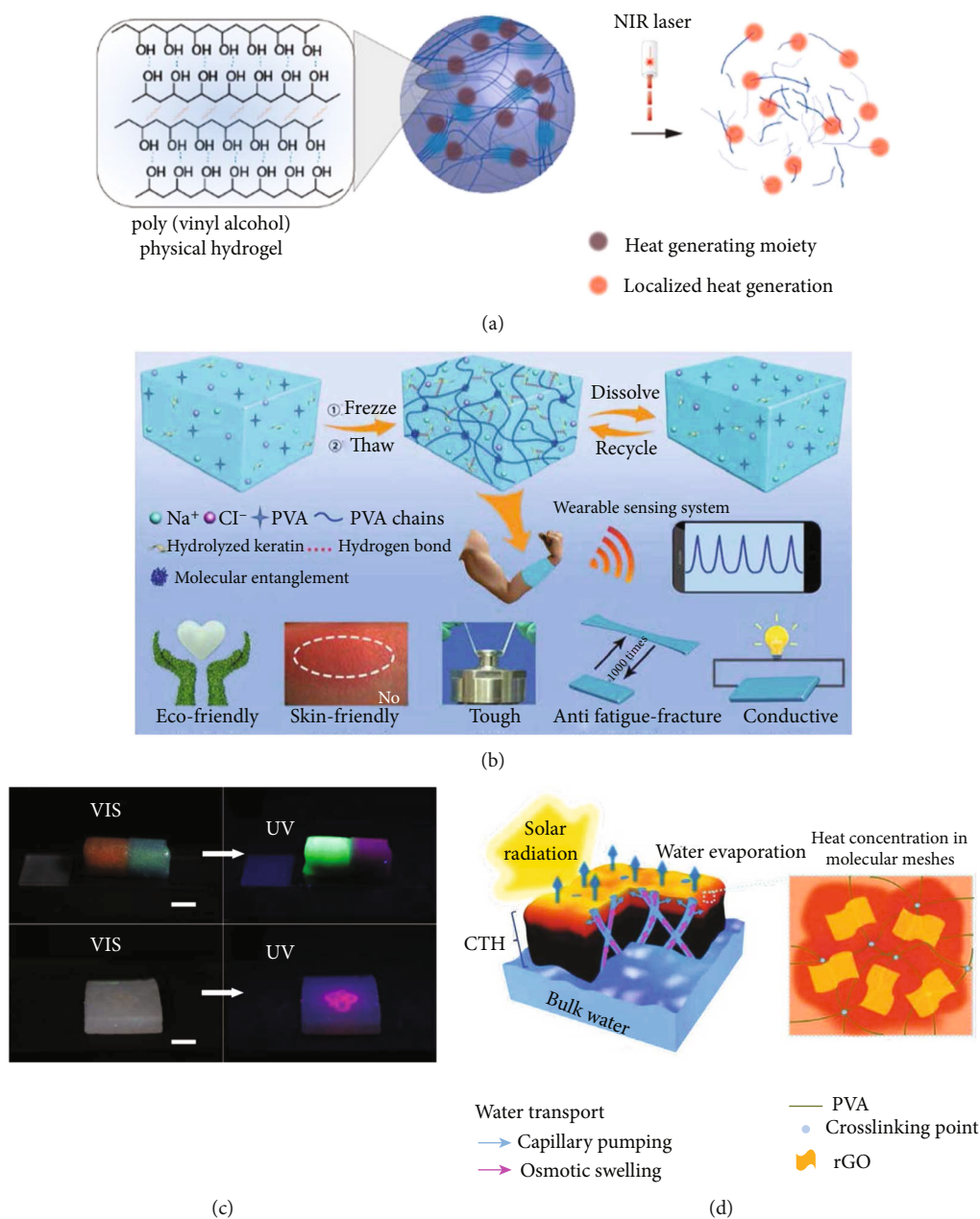


FIGURE 6: PVA-based functional hydrogels with their applications in: (a) remote triggered liquefaction [127], (b) biocompatible and wearable skin sensors [120], (c) anticounterfeiting materials [135], and (d) solar water purification [139].

**3.4.5. Other Applications.** In addition to the intensive studies and reports described above, there are more interesting studies showing specific properties of PVA materials that deserve attention. Such as an ultrastrong nacre-inspired double network PVA hydrogel with the impact-resistance property was reported [125]. There are also important applications in water treatment, such as high-efficiency removal of pollutants in wastewater and simple two-step preparation of PVA-based double network hydrogels as gel adsorbents to adsorb heavy metal ions in wastewater [126]. The crucial mechanism is that heavy metal ions form chelating bonds with hydrogen and excess hydroxyl groups in the PVA-

based hydrogel, thus, are finally removed from the water by being adsorbed. Such PVA-based double network hydrogel has good reusability as a chemical adsorbent. Moreover, it can also remove anions and cations and organic pollutants in dye wastewater. Very meaningful research results including remote liquefaction (Figure 6(a)) [127], molecular ink [128], contact lens sensor [129], and so on [130–133] are also reported. As a biocompatible polymer, PVA-based hydrogels prepared with bimetallic ions as crosslinking agents have high water retention properties, excellent mechanical strength, and self-healing properties and have also been studied for artificial skin and wearable sensor

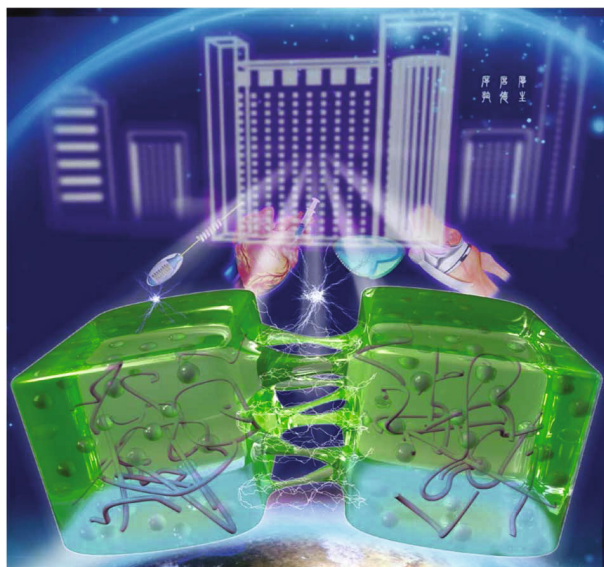


FIGURE 7: PVA-based hydrogels as multifunctionalized materials.

devices (Figure 6(b)) [120, 134]. Moreover, in the aspect of anticounterfeiting, it is also reported that the self-healable PVA hydrogel can display embedded fluorescent color under ultraviolet, as shown in Figure 6(c) [135]. In addition to some of the applications mentioned above, it is also reported that PVA-based diffusion membranes can be used in many separation processes. For instance, a composite membrane prepared with PVA as a skeleton and glutaraldehyde as a cross-linking agent is used as an anion channel for the recovery of acid or alkali solutions [136], besides, interesting works such as solar water purification [137, 138], seawater desalination (Figure 6(d)) [139], and oil/water separation [140] are also reported. Most recently, biomimetic tendon materials based on PVA have also been reported, showing more application prospects of PVA [141].

#### 4. Conclusions and Perspectives

The future design of hydrogels should have the following advantages: (1) functionalized hydrogel materials should utilize nontoxic, biodegradable macromolecules, that is, good biocompatibility and biodegradability, and hydrogels can be self-healed to extend their lifecycles; (2) for tissue engineering, the mechanical properties (such as hardness and elasticity) and structure (such as porosity and density) of the hydrogels should be highly matched with the embedded tissues; (3) the injected or implanted hydrogels could be tracked *in vivo* that further expanding their biomedical applications; (4) development of the multifunctional hydrogels to meet the complex biological conditions *in vivo* and achieving synergy. PVA hydrogels have great potential for development and intensive application prospects due to their excellent physical and chemical properties. Meanwhile, further study of PVA hydrogels should focus on structural design and modification, especially the strengthening of the long-term biocompatibility and mechanical strength of the hydrogel materials.

The improvement of the preparation and processing technology of hydrogels also played a very positive role in improving their performance. During the past decade, 3D printing technology has developed rapidly, and 3D printing devices with different principles and materials have been developed one after another. Among them, smart materials are a kind of material that has attracted much attention recently. In 2013, the importance of developing 3D printing for multifunctional intelligent, responsive materials was emphasized, and the concept of 4D printing was proposed [142]. The printed materials can change with time under certain external stimuli (temperature, light, external force, or pH), which was considered as the fourth dimension [143], and PVA hydrogels showed the potentials in 3D/4D printings for future intelligent applications [144].

With the continuous development of hydrogel design and continuous improvement, as well as the optimization of processing and molding methods, the traditional PVA hydrogel materials keep revealing more possibilities, and the future potential of PVA is enormous as illustrated in Figure 7.

#### Conflicts of Interest

The authors declare no conflict of interest.

#### Authors' Contributions

M.W., J.B., and W. T. wrote the paper under the supervision of C.C.; and Z.D., K.S., D.L., J.Y., and S.H. revised the review paper. Menghan Wang and Jianzhong Bai contributed equally to this work.

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#### References

- [1] O. Wichterle and D. Lim, "Hydrophilic gels for biological use," *Nature*, vol. 185, no. 4706, pp. 117-118, 1960.
- [2] G. Chen, W. Tang, X. Wang, X. Zhao, C. Chen, and Z. Zhu, "Applications of hydrogels with special physical properties in biomedicine," *Polymers*, vol. 11, no. 9, p. 1420, 2019.
- [3] A. Thangprasert, C. Tansakul, N. Thuaksubun, and J. Meesane, "Mimicked hybrid hydrogel based on gelatin/PVA for tissue engineering in subchondral bone interface for osteoarthritis surgery," *Materials and Design*, vol. 183, no. 5, pp. 108113-108133, 2019.



- [4] Z. Y. Gong, G. P. Zhang, X. L. Zeng et al., "High-strength, tough, fatigue resistant, and self-healing hydrogel based on dual physically cross-linked network," *ACS Applied Materials & Interfaces*, vol. 8, no. 36, pp. 24030–24037, 2016.
- [5] C. Bilici, V. Can, U. Nöchel, M. Behl, A. Lendlein, and O. Okay, "Melt-processable shape-memory hydrogels with self-healing ability of high mechanical strength," *Macromolecules*, vol. 49, no. 19, pp. 7442–7449, 2016.
- [6] J. I. D. Agudelo, M. R. Ramirez, E. R. Henquin, and I. Rintoul, "Modelling of swelling of PVA hydrogels considering non-ideal mixing behaviour of PVA and water," *Journal of Materials Chemistry B*, vol. 7, pp. 4049–4054, 2019.
- [7] S. J. Ma, S. W. Wang, Q. Li, Y. T. Leng, L. H. Wang, and G. H. Hu, "A novel method for preparing poly(vinyl alcohol) hydrogels: preparation, characterization, and application," *Industrial & Engineering Chemistry Research*, vol. 56, no. 28, pp. 7971–7976, 2017.
- [8] T. Inoue, "Gelled vinyl alcohol polymers and articles therefrom," 1975, PAT: US3875302.
- [9] N. A. Peppas, "Turbidimetric studies of aqueous poly(vinyl alcohol) solutions," *Die Makromolekulare Chemie*, vol. 176, no. 11, pp. 3433–3440, 1975.
- [10] N. A. Peppas and E. W. Merrill, "Determination of interaction parameter  $\chi_1$ , for poly(vinyl alcohol) and water in gels crosslinked from solutions," *Journal of Polymer Science: Polymer Chemistry Edition*, vol. 14, no. 2, pp. 459–464, 1976.
- [11] N. A. Peppas and E. W. Merrill, "Crosslinked poly(vinyl alcohol) hydrogels as swollen elastic networks," *Journal of Applied Polymer Science*, vol. 21, no. 7, pp. 1763–1770, 1977.
- [12] N. A. Peppas and E. W. Merrill, "Development of semicrystalline poly(vinyl alcohol) hydrogels for biomedical applications," *Journal of Biomedical Materials Research*, vol. 11, no. 3, pp. 423–434, 1977.
- [13] Z. Chen, D. Zhao, B. Liu et al., "3D printing of multifunctional hydrogels," *Advanced Functional Materials*, vol. 29, no. 20, 2019.
- [14] B. Thavornyutikarn, N. Chantarapanich, K. Sitthiseripratip, G. A. Thouas, and Q. Z. Chen, "Bone tissue engineering scaffolding: computer aided scaffolding techniques," *Progress in Biomaterials*, vol. 3, no. 11, pp. 61–102, 2014.
- [15] H. Zhang, H. Xia, and Y. Zhao, "Poly(vinyl alcohol) hydrogel can autonomously self-heal," *ACS Macro Letters*, vol. 11, no. 1, pp. 1233–1236, 2012.
- [16] H. Y. Du and J. H. Zhang, "Solvent induced shape recovery of shape memory polymer based on chemically cross-linked poly(vinyl alcohol)," *Soft Matter*, vol. 6, no. 14, pp. 3370–3376, 2010.
- [17] S. M. Shaheen, K. Ukai, L. X. Dai, and K. Yamura, "Properties of hydrogels of atactic poly(vinyl alcohol)/NaCl/H<sub>2</sub>O system and their application to drug release," *Polymer International*, vol. 51, no. 2, pp. 1390–1397, 2002.
- [18] K. Yamaura, M. Fukuda, T. Tanaka, and T. Tanigami, "Effect of addition of saccharides on gelation of aqueous poly(vinyl alcohol) solutions," *Journal of Applied Polymer Science*, vol. 74, no. 5, pp. 1298–1303, 1999.
- [19] A. Kumar, R. Mishra, Y. Reinwald, and S. Bhat, "Cryogels: freezing unveiled by thawing," *Materials Today*, vol. 13, no. 11, pp. 42–44, 2010.
- [20] C. M. Hassan and N. A. Peppas, "Structure and morphology of freeze/thawed PVA hydrogels," *Macromolecules*, vol. 33, no. 7, pp. 2472–2479, 2000.
- [21] S. H. Hyon, W. I. Cha, and Y. Ikada, "Preparation of transparent poly(vinyl alcohol) hydrogel," *Polymer Bulletin*, vol. 22, no. 2, pp. 119–122, 1989.
- [22] A. E. Ivanov and L. Ljunggren, "Thin poly(vinyl alcohol) cryogels: reactive groups, macropores and translucency in microtiter plate assays," *Heliyon*, vol. 5, no. 11, 2019.
- [23] A. H. A. Wahab, A. P. M. Saad, M. N. Harun et al., "Developing functionally graded PVA hydrogel using simple freeze-thaw method for artificial glenoid labrum," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 91, pp. 406–415, 2018.
- [24] H. S. Mansur, C. M. Sadahira, A. N. Souza, and A. A. P. Mansur, "FTIR spectroscopy characterization of poly (vinyl alcohol) hydrogel with different hydrolysis degree and chemically crosslinked with glutaraldehyde," *Materials Science and Engineering: C*, vol. 28, no. 4, pp. 539–548, 2008.
- [25] A. M. AL-Sabagh and Z. Abdeen, "Preparation and characterization of hydrogel based on poly(vinyl alcohol) cross-linked by different cross-linkers used to dry organic solvents," *Journal of Polymers and the Environment*, vol. 18, no. 4, pp. 576–583, 2010.
- [26] J. S. Park, J. W. Park, and E. Ruckenstein, "On the viscoelastic properties of poly(vinyl alcohol) and chemically crosslinked poly(vinyl alcohol)," *Journal of Applied Polymer Science*, vol. 82, no. 7, pp. 1816–1823, 2001.
- [27] X. J. Zhu, Y. Zhang, J. Deng, and X. J. Luo, "Effect of glycerol on the properties of the cross-linked polyvinyl alcohol hydrogel beads," *ChemistrySelect*, vol. 3, no. 2, pp. 467–470, 2018.
- [28] A. Pangon, S. Saesoo, N. Saengkrit, U. Ruktanonchai, and V. Intasanta, "Multicarboxylic acids as environment-friendly solvents and in situ crosslinkers for chitosan/PVA nanofibers with tunable physicochemical properties and biocompatibility," *Carbohydrate Polymers*, vol. 138, pp. 156–165, 2016.
- [29] S. Ceylan, D. Göktürk, and N. Bölgen, "Effect of crosslinking methods on the structure and biocompatibility of polyvinyl alcohol/gelatin cryogels," *Bio-medical Materials and Engineering*, vol. 27, no. 4, pp. 327–340, 2016.
- [30] X. Jiang, C. Y. Wang, and Q. Han, "Molecular dynamic simulation on the state of water in poly(vinyl alcohol) hydrogel," *Computational and Theoretical Chemistry*, vol. 1102, no. 4, pp. 15–21, 2017.
- [31] Z. C. Wang, X. M. Han, Y. X. Wang et al., "Facile preparation of low swelling, high strength, self-healing and pH-responsive hydrogels based on the triple-network structure," *Frontiers of Materials Science*, vol. 13, no. 1, pp. 54–63, 2019.
- [32] L. H. Fan, H. Yang, J. Yang, M. Peng, and J. Hu, "Preparation and characterization of chitosan/gelatin/PVA hydrogel for wound dressings," *Carbohydrate Polymers*, vol. 146, pp. 427–434, 2016.
- [33] Y. C. Nho and K. R. Park, "Preparation and properties of PVA/PVP hydrogels containing chitosan by radiation," *Journal of Applied Polymer Science*, vol. 85, no. 8, pp. 1787–1794, 2002.
- [34] S. Kumaraswamy and S. H. Mallaiah, "Swelling and mechanical properties of radiation crosslinked au/PVA hydrogel nanocomposites," *Radiation Effects and Defects in Solids*, vol. 171, no. 11–12, pp. 869–878, 2016.
- [35] F. Ding, Y. Zou, S. Wu, and X. Zou, "Self-healing and tough hydrogels with conductive properties prepared through an



- interpenetrating polymer network strategy," *Polymer*, vol. 206, article 122907, 2020.
- [36] C. Chen, Y. Zhu, H. Bao et al., "Ethanol-assisted multi-sensitive poly(vinyl alcohol) photonic crystal sensor," *Chemical Communications*, vol. 47, pp. 5530–5532, 2011.
  - [37] X. Yang, D. Sha, L. Sun et al., "Charged group-modified poly(vinyl alcohol) hydrogels: preparation and antibacterial property," *Reactive and Functional Polymers*, vol. 154, 2020.
  - [38] X. Fang, Y. X. Li, X. Li et al., "Dynamic hydrophobic domains enable the fabrication of mechanically robust and highly elastic poly(vinyl alcohol)-based hydrogels with excellent self-healing ability," *ACS Materials Lett.*, vol. 2, no. 7, pp. 764–770, 2020.
  - [39] M. Muchová, L. Münster, Z. Capáková, V. Mikulcová, I. Kuřitka, and J. Vicha, "Design of dialdehyde cellulose cross-linked poly(vinyl alcohol) hydrogels for transdermal drug delivery and wound dressings," *Materials Science & Engineering C*, vol. 116, 2020.
  - [40] E. Farzinfar and A. Paydayesh, "Investigation of polyvinyl alcohol nanocomposite hydrogels containing chitosan nanoparticles as wound dressing," *International Journal of Polymeric Materials and Polymeric Biomaterials*, vol. 68, pp. 628–638, 2018.
  - [41] C. Chen, Y. Zhu, H. Bao, X. Yang, and C. Li, "Physically controlled cross-linking in gelated crystalline colloidal array photonic crystals," *ACS Applied Materials & Interfaces*, vol. 2, no. 5, pp. 1499–1504, 2010.
  - [42] P. Jiang, P. Lin, C. Yang, H. L. Qin, X. L. Wang, and F. Zhou, "3D printing of dual-physical cross-linking hydrogel with ultrahigh strength and toughness," *Chemistry of Materials*, vol. 32, no. 23, pp. 9983–9995, 2020.
  - [43] C. Chen, H. Zhu, H. Bao et al., "Solvent-assisted poly(vinyl alcohol) gelated crystalline colloidal array photonic crystals," *Soft Matter*, vol. 7, no. 3, pp. 915–921, 2011.
  - [44] Y. Li, Chengxin Hu, J. Lan et al., "Hydrogel-based temperature sensor with water retention, frost resistance and remoldability," *Polymer*, vol. 186, article 122027, 2020.
  - [45] Y.-C. Nho, Y.-M. Lim, H.-J. Gwon, and E.-K. Choi, "Preparation and characterization of PVA/PVP/glycerin/antibacterial agent hydrogels using  $\gamma$ -irradiation followed by freeze-thawing," *Korean Journal of Chemical Engineering*, vol. 26, no. 6, pp. 1675–1678, 2009.
  - [46] X. Hu, L. Fan, G. Qin et al., "Flexible and low temperature resistant double network alkaline gel polymer electrolyte with dual-role KOH for supercapacitor," *Journal of Power Sources*, vol. 414, pp. 201–209, 2019.
  - [47] M. A. Darabi, A. Khosrozadeh, Y. Wang et al., "An alkaline based method for generating crystalline, strong, and shape memory polyvinyl alcohol biomaterials," *Advancement of Science*, vol. 7, 2020.
  - [48] C. Chen, Z. Q. Dong, G. C. Mei, Z. H. Li, and Z. G. Zhu, "One-pot preparation of physical hydrogel-based photonic crystal," *Materials Science Forum*, vol. 939, pp. 127–132, 2018.
  - [49] S. F. Chin, A. N. B. Romainor, S. C. Pang, and S. Lihan, "Antimicrobial starch-citrate hydrogel for potential applications as drug delivery carriers," *Journal of Drug Delivery Science and Technology*, vol. 54, 2019.
  - [50] M. E. Diken, B. K. Kizilduman, B. Y. Kardaş et al., "Synthesis, characterization, and their some chemical and biological properties of PVA/PAA/nPS hydrogel nanocomposites: hydrogel and wound dressing," *Journal of Bioactive and Compatible Polymers*, vol. 35, no. 3, pp. 203–215, 2020.
  - [51] X. Li, S. Dong, H. Yan, and C. Wu, "Fabrication and properties of PVA-TiO<sub>2</sub> hydrogel composites," *Procedia Engineering*, vol. 27, pp. 1488–1491, 2012.
  - [52] O. Kulikov, K. Hornung, and M. Wagner, "Novel processing additives for rotational molding of polyethylene," *Iranian Polymer Journal*, vol. 24, no. 5, pp. 452–462, 2009.
  - [53] J. Li, X. Li, S. Long, H. Li, and D. Huang, "Friction behavior of 3D printing SiO<sub>2</sub>/PVA hydrogel scaffold," *Acta Materialiae Compositae Sinica*, vol. 33, no. 11, pp. 2412–2418, 2016.
  - [54] M. Huang, Y. Hou, Y. B. Li, D. Q. Wang, and L. Zhang, "High performances of dual network PVA hydrogel modified by PVP using borax as the structure-forming accelerator," *Designed Monomers and Polymers*, vol. 20, no. 1, pp. 505–513, 2017.
  - [55] M. Sareethammanuwat, S. Boonyeun, and P. Arpornmaeklong, "Effects of beta-tricalcium phosphate nanoparticles on the properties of athermosensitive chitosan/collagen hydrogel and controlled release of quercetin," *Journal of Biomedical Materials Research Part A*, vol. 109, no. 7, pp. 1147–1159, 2021.
  - [56] X. Wu, Y. Xie, C. Xue et al., "Preparation of PVA-GO composite hydrogel and effect of ionic coordination on its properties," *Materials Research Express*, vol. 6, no. 7, 2019.
  - [57] Y. Meng, J. Cao, Y. Chen, Y. Yu, and L. Ye, "3D printing of a poly(vinyl alcohol)-based nano-composite hydrogel as an artificial cartilage replacement and the improvement mechanism of printing accuracy," *Journal of Materials Chemistry B*, vol. 8, pp. 677–690, 2020.
  - [58] K. Kalantari, E. Mostafavi, B. Saleh, P. Soltantabar, and T. J. Webster, "Chitosan/PVA hydrogels incorporated with green synthesized cerium oxide nanoparticles for wound healing applications," *European Polymer Journal*, vol. 134, 2020.
  - [59] Z. Sun, C. Song, C. Wang, Y. Hu, and J. Wu, "Hydrogel-based controlled drug delivery for cancer treatment: a review," *Molecular Pharmaceutics*, vol. 17, no. 2, pp. 373–391, 2020.
  - [60] M. S. B. Husain, A. Gupta, B. Y. Alash, and S. Sharma, "Synthesis of PVA/PVP based hydrogel for biomedical applications: a review," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 40, no. 20, pp. 2388–2393, 2018.
  - [61] A. S. Hoffman, "Hydrogels for biomedical applications," *Advanced Drug Delivery Reviews*, vol. 54, no. 1, pp. 3–12, 2012.
  - [62] Y. Jiang, Y. Hou, J. Fang et al., "Preparation and characterization of PVA/SA/HA composite hydrogels for wound dressing," *International Journal of Polymer Analysis and Characterization*, vol. 24, pp. 132–141, 2019.
  - [63] R. Gauvin, Y. C. Chen, J. W. Lee et al., "Microfabrication of complex porous tissue engineering scaffolds using 3D projection stereolithography," *Biomaterials*, vol. 33, no. 15, pp. 3824–3834, 2012.
  - [64] T. Y. Wang, Y. J. Sheng, and H. K. Tsao, "Donnan potential of dilute colloidal dispersions: Monte Carlo simulations," *Journal of Colloid and Interface Science*, vol. 340, no. 2, pp. 192–201, 2009.
  - [65] T. Casalini and G. Perale, "From microscale to macroscale: nine orders of magnitude for a comprehensive modeling of hydrogels for controlled drug delivery," *Gels*, vol. 5, p. 28, 2019.

- [66] J. E. Möckel and B. C. Lippold, "Zero-order drug release from hydrocolloid matrices," *Pharmaceutical Research*, vol. 10, no. 7, pp. 1066–1070, 1993.
- [67] M. Kuddushi, D. Ray, V. Aswal, C. Hoskins, and N. Malek, "Poly(vinyl alcohol) and functionalized ionic liquid-based smart hydrogel for doxorubicin release ACS," *Applied Bio Materials*, vol. 3, no. 8, pp. 4883–4894, 2020.
- [68] C. Chen, X. L. Zhao, Z. H. Li, Z. G. Zhu, S. H. Qian, and A. J. Flewitt, "Current and emerging technology for continuous glucose monitoring," *Sensors*, vol. 17, p. 182, 2017.
- [69] Y. Cai, J. Che, M. Yuan, X. Shi, W. Chen, and W. E. Yuan, "Effect of glycerol on sustained insulin release from PVA hydrogels and its application in diabetes therapy," *Experimental and Therapeutic Medicine*, vol. 12, pp. 2039–2044, 2016.
- [70] Y. Li, C. Zhu, D. Fan et al., "A bi-layer PVA/CMC/PEG hydrogel with gradually changing pore sizes for wound dressing," *Macromolecular Bioscience*, vol. 19, p. 1800424, 2019.
- [71] J. Li, F. Yu, G. Chen et al., "Moist-retaining, self-recoverable, bioadhesive, and transparent in situ forming hydrogels to accelerate wound healing," *ACS Applied Materials & Interfaces*, vol. 12, pp. 2023–2038, 2020.
- [72] K. Bialik-was, K. Pluta, D. Malina, and T. M. Majka, "Alginate/PVA-based hydrogel matrices with Echinacea purpurea extract as a new approach to dermal wound healing," *International Journal of Polymeric Materials and Polymeric Biomaterials*, vol. 70, pp. 195–206, 2019.
- [73] X. Li, Y. Jiang, F. Wang et al., "Preparation of polyurethane/polyvinyl alcohol hydrogel and its performance enhancement via compositing with silver particles," *RSC Advances*, vol. 7, pp. 46480–46485, 2017.
- [74] S. Sakai, M. Tsumura, M. Inoue, Y. Koga, K. Fukano, and M. Taya, "Polyvinyl alcohol-based hydrogel dressing gellable on-wound via a co-enzymatic reaction triggered by glucose in the wound exudate," *Journal of Materials Chemistry B*, vol. 1, pp. 5067–5075, 2013.
- [75] S. P. Lin, K. Y. Lo, T. N. Tseng, J. M. Liu, T. Y. Shih, and K. C. Cheng, "Evaluation of PVA/dextran/chitosan hydrogel for wound dressing," *Cellular Polymers*, vol. 38, pp. 15–30, 2019.
- [76] A. Shamloo, Z. Aghababae, H. Afjoul et al., "Fabrication and evaluation of chitosan/gelatin/PVA hydrogel incorporating honey for wound healing applications: an in vitro, in vivo study," *International Journal of Pharmaceutics*, vol. 592, article 120068, 2021.
- [77] S. Chen, H. Wang, Z. Jian et al., "Novel poly(vinyl alcohol)/chitosan/modified graphene oxide biocomposite for wound dressing application," *Macromolecular Bioscience*, vol. 20, p. 1900385, 2020.
- [78] D. N. Iqbal, S. Shafiq, S. M. Khan et al., "Novel chitosan/guar gum/PVA hydrogel: preparation, characterization and antimicrobial activity evaluation," *International Journal of Biological Macromolecules*, vol. 64, pp. 499–509, 2020.
- [79] X. H. Zhang, Z. Yin, Y. Guo et al., "Facile and large-scale synthesis of PVA/chitosan/collagen hydrogel for wound healing," *New Journal of Chemistry*, vol. 44, pp. 20776–20784, 2020.
- [80] E. A. Kamoun, E. S. Kenawy, and X. Chen, "A review on polymeric hydrogel membranes for wound dressing applications: PVA-based hydrogel dressings," *Journal of Advanced Research*, vol. 8, no. 3, pp. 217–233, 2017.
- [81] A. Poliakov, V. Pakhaliuk, and V. L. Popov, "Current trends in improving of artificial joints design and technologies for their arthroplasty," *Frontiers of Mechanical Engineering*, vol. 6, p. 4, 2020.
- [82] S. Ma, M. Scaraggi, D. Wang et al., "Nanoporous substrate-infiltrated hydrogels: a bioinspired regenerable surface for high load bearing and tunable friction," *Advanced Functional Materials*, vol. 25, no. 47, pp. 7366–7374, 2015.
- [83] P. Lin, R. Zhang, X. Wang et al., "Articular cartilage inspired bilayer tough hydrogel prepared by interfacial modulated polymerization showing excellent combination of high load-bearing and low friction performance," *ACS Macro Letters*, vol. 5, no. 11, pp. 1191–1195, 2016.
- [84] W. Lan, M. Xu, X. Zhang et al., "Biomimetic polyvinyl alcohol/type II collagen hydrogels for cartilage tissue engineering," *Journal of Biomaterials Science, Polymer Edition*, vol. 31, pp. 1179–1198, 2020.
- [85] T. Murakami, S. Yarimitsu, K. Nakashima, T. Yamaguchi, Y. Sawae, and N. Sakai, "Suzuki, Atsushi. Superior lubricity in articular cartilage and artificial hydrogel cartilage," *Proceeding of the Institution of Mechanical Engineers Part J: Journal of Engineering Tribology*, vol. 228, no. 10, pp. 1099–1111, 2014.
- [86] J. M. Lee, T. Sultan, S. H. Kim et al., "Artificial auricular cartilage using silk fibroin and polyvinyl alcohol hydrogel," *International Journal of Molecular Sciences*, vol. 18, p. 1707, 2017.
- [87] E. Dattola, E. I. Parrotta, S. Scalise et al., "Development of 3D PVA scaffolds for cardiac tissue engineering and cell screening applications," *RSC Advances*, vol. 9, pp. 4246–4257, 2019.
- [88] H. Zhou, D. Xiong, W. Tong, Z. Shi, and X. Xiong, "Lubrication behaviors of PVA-casted LSPEEK hydrogels in artificial cartilage repair," *Journal of Applied Polymer Science*, vol. 136, p. 47944, 2019.
- [89] J. K. Katta, M. Marcolongo, A. Lowman, and K. A. Mansmann, "Friction and wear behavior of poly(vinyl alcohol)/poly(vinyl pyrrolidone) hydrogels for articular cartilage replacement," *Journal of Biomedical Materials Research Part A*, vol. 83A, no. 2, pp. 471–479, 2007.
- [90] K. Chen, X. Yang, D. Zhang, L. Xu, X. Zhang, and Q. Wang, "Biotribology behavior and fluid load support of PVA/HA composite hydrogel as artificial cartilage," *Wear*, vol. 376–377, pp. 329–336, 2017.
- [91] T. Hayami, K. Matsumura, M. Kusunoki, H. Nishikawa, and S. Hontsu, "Imparting cell adhesion to poly (vinyl alcohol) hydrogel by coating with hydroxyapatite thin film," *Materials Letters*, vol. 61, no. 13, pp. 2667–2670, 2007.
- [92] H. A. Awad, M. Q. Wickham, H. A. Leddy, J. M. Gimble, and F. Guilak, "Chondrogenic differentiation of adipose-derived adult stem cells in agarose, alginate, and gelatin scaffolds," *Biomaterials*, vol. 25, no. 16, pp. 3211–3222, 2004.
- [93] S. Moscato, L. Matti, D. D'Alessandro et al., "Interaction of human gingival fibroblasts with PVA/gelatin sponges," *Micron*, vol. 39, no. 5, pp. 569–579, 2008.
- [94] M. G. Drozdova, D. S. Zaytseva-Zotova, R. A. Akasov et al., "Macroporous modified poly (vinyl alcohol) hydrogels with charged groups for tissue engineering: preparation and in vitro evaluation," *Materials Science and Engineering C*, vol. 75, pp. 1075–1082, 2017.
- [95] L. Guo, H. Zhang, D. Fortin, H. Xia, and Y. Zhao, "Poly(vinyl alcohol)-poly(ethylene glycol) double-network hydrogel: a

- general approach to shape memory and self-healing functionalities," *Langmuir*, vol. 31, no. 42, pp. 11709–11716, 2015.
- [96] O. Okay, "How to design both mechanically strong and self-healable hydrogels?," in *Advances in Polymer Science*, pp. 21–62, Springer, 2020.
- [97] G. Zhang, T. Ngai, Y. Deng, and C. Wang, "An injectable hydrogel with excellent self-healing property based on quadruple hydrogen bonding," *Macromolecular Chemistry and Physics*, vol. 217, no. 19, pp. 2172–2181, 2016.
- [98] S. Wang, Y. Lv, S. Feng, Q. Li, and T. Zhang, "Bimetallic ions synergistic cross-linking high-strength rapid self-healing antibacterial hydrogel," *Polymer Engineering and Science*, vol. 59, p. 25037, 2019.
- [99] S. Mukherjee, M. R. Hilla, and B. S. Sumerlin, "Self-healing hydrogels containing reversible oxime crosslinks," *Soft Matter*, vol. 11, no. 30, pp. 6152–6161, 2015.
- [100] L. He, D. Szopinski, Y. Wu, G. A. Luinstra, and P. Theato, "Toward self-healing hydrogels using one-pot thiol-ene click and borax-diol chemistry," *ACS Macro Letters*, vol. 4, no. 7, pp. 673–678, 2015.
- [101] S. Spoljaric, A. Salminen, N. D. Luong, and J. Seppälä, "Stable, self-healing hydrogels from nanofibrillated cellulose, poly(vinyl alcohol) and borax via reversible crosslinking," *European Polymer Journal*, vol. 56, pp. 105–117, 2014.
- [102] B. Lu, F. Lin, X. Jiang et al., "One-pot assembly of microfibrillated cellulose reinforced PVA–borax hydrogels with self-healing and pH-responsive properties," *ACS Sustainable Chemistry & Engineering*, vol. 5, no. 1, pp. 948–956, 2017.
- [103] J. P. Xu, Y. Liu, and S. H. Hsu, "Hydrogels based on Schiff base linkages for biomedical applications," *Molecules*, vol. 24, no. 16, p. 3005, 2019.
- [104] Y. Wang, Q. B. Chen, M. Chen, Y. Guan, and Y. J. Zhang, "PHEMA hydrogel films crosslinked with dynamic disulfide bonds: synthesis, swelling-induced mechanical instability and self-healing," *Polymer Chemistry*, vol. 10, no. 35, pp. 4844–4851, 2019.
- [105] Y. Wang, Z. Wang, K. Wu et al., "Synthesis of cellulose-based double-network hydrogels demonstrating high strength, self-healing, and antibacterial properties," *Carbohydrate Polymers*, vol. 168, pp. 112–120, 2017.
- [106] Y. Wang, J. Niu, J. Hou et al., "A novel design strategy for triple-network structure hydrogels with high-strength," *Tough and Self-Healing Properties. Polymer*, vol. 135, pp. 16–24, 2018.
- [107] Y. Wang, J. Yan, Z. Wang et al., "One-pot fabrication of triple-network structure hydrogels with high-strength and self-healing properties," *Materials Letters*, vol. 207, pp. 53–56, 2017.
- [108] H. Wada, K. Yoshikawa, S. Nohara et al., "Electrochemical characteristics of new electric double layer capacitor with acidic polymer hydrogel electrolyte," *Journal of Power Sources*, vol. 159, pp. 1464–1467, 2006.
- [109] D. Wang, L. Wang, and L. Yu, "Synthesis of three-dimensional polyacrylamide/poly(vinylalcohol) hydrogel and its application in supercapacitor," *Materials Review*, vol. 32, no. 17, pp. 2907–2911, 2018.
- [110] H. Yu, N. Rouelle, A. Qiu et al., "Hydrogen bonding reinforced hydrogel electrolyte for flexible, robust and all-in-one supercapacitor with excellent low-temperature tolerance," *ACS Applied Materials & Interfaces*, vol. 12, no. 34, pp. 37977–37985, 2020.
- [111] Z. Wang, F. Tao, and Q. Pan, "A self-healable polyvinyl alcohol-based hydrogel electrolyte for smart electrochemical capacitors," *Journal of Materials Chemistry A*, vol. 4, no. 45, pp. 17732–17739, 2016.
- [112] G. Cai, J. Wang, K. Qian, J. Chen, S. Li, and P. S. Lee, "Extremely stretchable strain sensors based on conductive self-healing dynamic cross-links hydrogels for human-motion detection," *Advancement of Science*, vol. 4, no. 2, p. 1600190, 2017.
- [113] W. Li, X. Li, X. Zhang et al., "Flexible poly(vinyl alcohol)–polyaniline hydrogel film with vertically aligned channels for an integrated and self-healable supercapacitor," *ACS Applied Energy Materials*, vol. 3, no. 9, pp. 9408–9416, 2020.
- [114] Q. Rong, W. Lei, L. Chen, Y. Yin, J. Zhou, and M. Liu, "Anti-freezing, conductive self-healing organohydrogels with stable strain-sensitivity at subzero temperatures," *Angewandte Chemie, International Edition*, vol. 56, pp. 14159–14163, 2017.
- [115] Y. Ye, Y. Zhang, Y. Chen, X. Han, and F. Jiang, "Cellulose nanofibrils enhanced, strong, stretchable, freezing-tolerant ionic conductive organohydrogel for multi-functional sensors," *Advanced Functional Materials*, vol. 30, p. 2003430, 2020.
- [116] S. Azadi, S. Peng, S. A. Moshizi et al., "Biocompatible and highly stretchable PVA/AgNWs hydrogel strain sensors for human motion detection," *Advanced Materials Technologies*, vol. 5, no. 11, p. 2000426, 2020.
- [117] X. Jing, H. Li, H.-Y. Mi et al., "Highly transparent, stretchable, and rapid self-healing polyvinyl alcohol/cellulose nanofibril hydrogel sensors for sensitive pressure sensing and human motion detection," *Sensors and Actuators B: Chemical*, vol. 295, pp. 159–167, 2019.
- [118] Y. Wang, L. Zhang, and A. Lu, "Highly stretchable, transparent cellulose/PVA composite hydrogel for multiple sensing and triboelectric nanogenerators," *Journal of Materials Chemistry A*, vol. 8, p. 13935, 2020.
- [119] F. Ye, M. Li, D. Ke, L. Wang, and Y. Lu, "Ultrafast self-healing and injectable conductive hydrogel for strain and pressure sensors," *Advanced Materials Technologies*, vol. 4, no. 9, p. 1900346, 2019.
- [120] Y. Gao, S. Gu, F. Jia, and G. Gao, "A skin-matchable, recyclable and biofriendly strain sensor enabled by hydrolyzed keratin-assisted hydrogel," *Journal of Materials Chemistry A*, vol. 8, pp. 24175–24183, 2020.
- [121] C. Chen, Z. Dong, H. Chen, Y. Chen, Z. Zhu, and W. H. Shih, "Two-dimensional photonic crystals," *Progress in Chemistry*, vol. 30, no. 6, pp. 775–784, 2018.
- [122] W. Tang and C. Chen, "Hydrogel-based colloidal photonic crystal devices for glucose sensing," *Polymers*, vol. 12, p. 625, 2020.
- [123] M. M. W. Muscatello and S. A. Asher, "Poly(vinyl alcohol) rehydratable photonic crystal sensor material," *Advanced Functional Materials*, vol. 18, no. 8, pp. 1186–1193, 2008.
- [124] C. Chen, Z.-Q. Dong, J.-H. Shen, H.-W. Chen, Y.-H. Zhu, and Z.-G. Zhu, "2D photonic crystal hydrogel sensor for tear glucose monitoring," *ACS Omega*, vol. 3, no. 3, pp. 3211–3217, 2018.
- [125] X. Zhao, M. Wang, Y. Chen et al., "Puncture-resistant hydrogel: placing molecular complexes along phase boundaries," *ACS Applied Materials & Interfaces*, vol. 11, no. 21, pp. 19421–19428, 2019.

- [126] L. Chu, C. Liu, G. Zhou et al., "A double network gel as low cost and easy recycle adsorbent: highly efficient removal of Cd(II) and Pb(II) pollutants from wastewater," *Journal of Hazardous Materials*, vol. 300, pp. 153–160, 2015.
- [127] S. L. Pedersen, T. H. Huynh, P. Pöschko et al., "Remotely triggered liquefaction of hydrogel," *Materials. ACS Nano*, vol. 14, no. 7, pp. 9145–9155, 2020.
- [128] R. Nishiyabu, M. Tomura, T. Okadea, and Y. Kubo, "Boronic acids as molecular inks for surface functionalization of polyvinyl alcohol substrates," *New Journal of Chemistry*, vol. 42, pp. 7392–7398, 2018.
- [129] X.-J. Zha, S.-T. Zhang, J.-H. Pu et al., "Nanofibrillar poly(vinyl alcohol) ionic organohydrogels for smart contact lens and human-interactive sensing," *ACS Applied Materials & Interfaces*, vol. 12, no. 20, pp. 23514–23522, 2020.
- [130] N. More, D. Ranglani, S. Kharche, and G. Kapusetti, "Electrospun mat of thermal-treatment-induced nanocomposite hydrogel of polyvinyl alcohol and cerium oxide for biomedical applications," *Journal of Applied Polymer Science*, vol. 137, article e49426, 2020.
- [131] L. Wu, S. Huang, J. Zheng, Z. Qiu, X. Lin, and Y. Qin, "Synthesis and characterization of biomass lignin-based PVA super-absorbent hydrogel," *International Journal of Biological Macromolecules*, vol. 140, pp. 538–545, 2019.
- [132] S. Lin, X. Liu, J. Liu et al., "Anti-fatigue-fracture hydrogels," *Science Advances*, vol. 5, p. eaau8528, 2019.
- [133] T. Hua, J. Sun, Y. Zhang et al., "PVA-assisted hydrated vanadium pentoxide/reduced graphene oxide films for excellent Li<sup>+</sup> and Zn<sup>2+</sup> storage properties," *Journal of Materials Science & Technology*, vol. 83, pp. 7–17, 2021.
- [134] S. Wang, Q. Li, S. Feng, Y. Lv, and T. Zhang, "A water-retaining, self-healing hydrogel as ionic skin with a highly pressure sensitive properties," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 104, pp. 318–329, 2019.
- [135] X. Wang, Y. Qiu, G. Chen et al., "Self-healable poly(vinyl alcohol) photonic crystal hydrogel," *ACS Applied Polymer Materials*, vol. 2, no. 5, pp. 2086–2092, 2020.
- [136] W. Ji, N. U. Afsar, B. Wu et al., "In-situ crosslinked SPPO/PVA composite membranes for alkali recovery via diffusion dialysis," *Journal of Membrane Science*, vol. 590, article 117267, 2019.
- [137] F. Zhao, X. Zhou, Y. Shi et al., "Highly efficient solar vapour generation via hierarchically nanostructured gels," *Nature Nanotech.*, vol. 13, pp. 489–495, 2018.
- [138] Y. Guo, H. Lu, F. Zhao, X. Zhou, W. Shi, and G. Yu, "Biomass-derived hybrid hydrogel evaporators for cost-effective solar water purification," *Advanced Materials*, vol. 32, p. 1907061, 2020.
- [139] X. Zhou, F. Zhao, Y. Guo, Y. Zhang, and G. Yu, "A hydrogel-based antifouling solar evaporator for highly efficient water desalination," *Energy & Environmental Science*, vol. 11, pp. 1985–1992, 2018.
- [140] K. Thakur, A. Rajhans, and B. Kandasubramanian, "Starch/PVA hydrogels for oil/water separation," *Environmental Science and Pollution Research*, vol. 26, pp. 32013–32028, 2019.
- [141] M. Hua, S. Wu, Y. Ma et al., "Strong tough hydrogels via the synergy of freeze-casting and salting out," *Nature*, vol. 590, pp. 594–599, 2021.
- [142] S. Tibbits, "4D printing: multi-material shape change," *Architectural Design*, vol. 84, no. 1, pp. 116–121, 2014.
- [143] Y. S. Lui, W. T. Sow, L. P. Tan, Y. Wu, Y. Lai, and H. Li, "4D printing and stimuli-responsive materials in biomedical aspects," *Acta Biomaterialia*, vol. 92, pp. 19–36, 2019.
- [144] M. Hua, D. Wu, S. Wu, Y. Ma, A. Alsaied, and X. He, "4D printable tough and thermoresponsive hydrogels," *ACS Applied Materials & Interfaces*, vol. 13, no. 11, pp. 12689–12697, 2021.