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Recent Advances in Polyvinyl Alcohol-Based Hydrogels for Antibacterial Medical Dressings

Leyi Hou

School of Materials Science and Engineering, Donghua University, Shanghai, 201620, China

Abstract. Polyvinyl alcohol (PVA) hydrogels have become widely utilized materials in the field of antibacterial medical dressings owing to their outstanding mechanical properties, excellent biocompatibility, and simple preparation processes, as well as their biodegradability and ease of modification. This paper first introduces the preparation methods of PVA hydrogels, then elaborates on the research progress of PVA hydrogel-based antibacterial dressings according to their classification, and finally discusses the current limitations and future development trends of PVA hydrogels in biomedical applications.

Keywords: Polyvinyl alcohol; Hydrogel; Antibacterial medical dressing.

1. Introduction

During the wound healing process, bacterial infections can easily occur, while the overuse of traditional synthetic antibiotics has aggravated the problem of bacterial resistance[1]. Infectious diseases caused by drug-resistant bacterial strains have seriously threatened human life and health, posing a major challenge to public health security. In antibacterial applications, biomedical dressings with good antibacterial properties can replace antibiotics to reduce problems associated with antibiotic usage[2]. Biomedical dressings are required to exhibit excellent biocompatibility, help maintain a moist wound environment, continuously absorb wound exudates, and effectively avoid secondary damage to the wound caused by frequent dressing replacement[3]. At present, various types of biomedical dressings are available on the market, including foams, films, fibers, hydrogels, hydrocolloids, and sponges, each differing in swelling capacity, mechanical properties, and other characteristics[4].

Hydrogels are soft materials composed of hydrophilic polymers that form three-dimensional network structures. Such materials are usually prepared from long-chain hydrophilic polymers such as polyethylene glycol (PEG), polyvinyl alcohol (PVA), sodium alginate (Alg), and hyaluronic acid (HA), which are crosslinked physically or chemically[5]. This unique crosslinked network structure endows hydrogels with two essential features: on the one hand, they can absorb and retain water hundreds of times their own weight; on the other hand, they can maintain a stable three-dimensional framework without dissolving[6]. Because their properties resemble those of human soft tissue and they possess a porous network, hydrogels are often applied in biomedical fields such as drug delivery, tissue engineering, and gene carriers[7–9]. As biomedical dressings, hydrogels have excellent exudate absorption, rapid hemostasis, suitable water vapor permeability, and good biocompatibility, and have been widely used in the treatment of chronic wounds[10].

PVA is a long-chain polymer containing a large number of hydroxyl groups along the molecular chains, forming strong intra- and intermolecular hydrogen bonds that confer high hydrophilicity. In addition, PVA has good biodegradability, film-forming ability, and antibacterial properties, and is inexpensive, making it an excellent material for the preparation of biomedical dressings[11]. PVA hydrogels combine the advantages of both components: they are non-toxic, non-polluting, highly antibacterial, and biocompatible. They can maintain a moist wound environment and be tailored to cover wounds of various sizes. Their strong adsorption capacity enables absorption of wound secretions, preventing necrosis, avoiding infection-induced inflammation, and promoting healing. Moreover, they possess excellent film-forming ability, good flexibility, and breathability, can degrade slowly, and are harmless to the human body. This paper first describes the preparation methods of PVA hydrogels, then elaborates on the research progress of PVA hydrogels in antibacterial medical

dressings based on their classification, and finally provides an outlook on their future development directions.

2. Preparation Methods of PVA Hydrogels

2.1 Physical Crosslinking

The physical crosslinking method connects molecular chains through non-covalent interactions such as electrostatic forces, ionic bonds, and hydrogen bonds, forming a three-dimensional network structure. Among them, the cyclic freeze-thaw method is the most commonly used preparation technique, which involves repeatedly freezing and thawing polymer aqueous solutions to promote the formation of hydrogen bonds and entanglements between molecular chains, thereby generating physically crosslinked hydrogels[12−14].

The advantage of the physical crosslinking method lies in the reversibility and self-healing ability of the formed network structure, and it does not require the use of toxic chemical crosslinking agents. Therefore, the obtained hydrogels generally exhibit good biocompatibility and low toxicity, making them suitable for applications in medical materials and related fields. However, physically crosslinked hydrogels also face several issues, such as structural instability, relatively low mechanical strength, and difficulty in precisely controlling pore size[15].

2.2 Chemical Crosslinking

The chemical crosslinking method constructs a hydrogel network structure by initiating chemical reactions through the active functional groups of raw materials or by introducing crosslinking agents. The reaction mechanisms include various types such as free radical polymerization, Schiff base reaction, and click chemistry[16],[17]. Commonly used crosslinking agents include aldehydes (e.g., glutaraldehyde), borates, epichlorohydrin, and heavy metal oxides, which can covalently bond with the hydroxyl or other active groups on the PVA polymer chains to form a stable three-dimensional crosslinked network[18−20].

Hydrogels prepared by chemical crosslinking possess significant structural stability and excellent mechanical properties. Their crosslinking points are uniformly distributed and can effectively resist biodegradation. However, the crosslinking agents used in the chemical crosslinking process are generally toxic, which may negatively affect the biocompatibility of the material. Additionally, unreacted crosslinkers or by-products may remain in the final product, reducing its purity and limiting its applications in biomedical fields[21].

2.3 Radiation Crosslinking

The radiation crosslinking method uses high-energy radiation to irradiate PVA solutions, generating macromolecular free radicals from the -CH_2- and -CH(OH)- groups in PVA molecules. These free radicals then form covalent bonds through radical coupling reactions, resulting in the gradual formation of PVA-based hydrogels[19, 22].

The advantage of the radiation crosslinking method is that it avoids the hazards associated with chemical reagents. The resulting hydrogel dressings exhibit high transparency, allowing direct observation of wound healing without removing the dressing. However, this method also has several drawbacks: the mechanical properties of the prepared hydrogels are often poor, many additives cannot be incorporated into the hydrogel due to the limitations of irradiation intensity, and the high technical cost makes it difficult to meet practical application requirements[23].

3. Research Progress of PVA Hydrogels

According to the type of antibacterial agent and the hydrogel matrix, PVA hydrogels can be divided into three categories: PVA hydrogels loaded with inorganic antibacterial materials, PVA hydrogels containing antibiotics, and PVA hydrogels with inherent antibacterial ability.

3.1 PVA Hydrogels Loaded with Inorganic Antibacterial Materials

The three-dimensional network of PVA hydrogels provides an ideal environment for the dissolution and sustained release of inorganic antibacterial materials, while also concentrating antibacterial activity at the wound site to achieve long-term antibacterial effects through synergy with inorganic components. Inorganic antibacterial materials are mainly classified into two groups: metallic nanoparticles (such as gold, silver, and copper) and metal oxide nanoparticles (such as zinc oxide, copper oxide, and titanium dioxide).

Metallic nanoparticles can release positively charged metal ions that are electrostatically attracted to the negatively charged bacterial cell membranes, leading to membrane disruption. Among these, silver nanoparticles (Ag-NPs) exhibit strong antibacterial activity against Escherichia coli and Staphylococcus aureus at low concentrations, and are currently the most widely used type of inorganic antibacterial material[24]. Zhang et al. prepared a PVACS/MOF/MXene hydrogel dressing by integrating chitosan, PVA, AgCu-H_2PYDC metal-organic frameworks (MOFs), and Ti_3C_2Tx MXene. This hydrogel exhibited high electrical conductivity and excellent antibacterial performance, killing E. coli and S. aureus within 12 hours. Under 1 V electrical stimulation, it promoted cell migration and angiogenesis while maintaining good mechanical strength and biocompatibility, offering an innovative strategy for the development of intelligent wound dressings[25].

However, the synthesis of Ag-NP-loaded hydrogels and the accumulation of metallic nanoparticles can pose risks to both the environment and human health. Therefore, green synthesis technologies or in situ loading methods have become important research directions in the antibacterial biomedical field. Song et al. introduced Ag-NPs as an antibacterial agent into a PVA/bacterial cellulose (BC) solution and prepared PVA/BC/Ag hydrogels via the freeze-thaw method, as shown in Fig. 1(a). The resulting hydrogel exhibited a porous three-dimensional network structure with high mechanical strength. In addition, it demonstrated excellent antibacterial activity and good biocompatibility, showing great potential for wound-healing applications[26]. Saravanan et al. synthesized reduced graphene oxide-silver nanoparticle (rGO-Ag-NP) composites via a hydrothermal method and incorporated them into a PVA matrix to fabricate a PVA-AgG nanocomposite hydrogel with a uniform porous structure, as shown in Fig. 1(b). Ag-NPs were stably anchored onto the rGO surface in crystalline form, enhancing thermal stability and structural uniformity. The hydrogel exhibited excellent biocompatibility and potent antibacterial activity against E. coli and S. aureus, showing great promise for bioactive wound dressing applications[27]. Abbasi et al. fabricated a novel hydrogel dressing via in situ growth by spraying 3-aminophenylboronic acid (PBA)-modified dialdehyde laminarin (LamPBA) with Ag-NP-impregnated PVA, as shown in Fig. 1(c). The resulting hydrogel exhibited excellent rheological properties and antibacterial activity, with antibacterial rates against E. coli and S. aureus reaching up to 80%. Moreover, it promoted cell proliferation and migration. Histological analysis confirmed that it facilitated epidermal regeneration, collagen deposition, antioxidant activity, and angiogenesis, indicating great potential for diabetic wound treatment[28].

Metal oxide nanoparticles can generate reactive oxygen species (ROS), which non-selectively attack all components of bacterial cells. In practical applications, they are often combined with metallic nanoparticles for enhanced antibacterial effects[24]. Madfoon et al. prepared a biocompatible hydrogel from natural polymers of xanthan gum and alginate, which was then combined with PVA and $ZnMnFe_2O_4$ nanoparticles to form a novel nanocomposite material with enhanced mechanical strength and antibacterial activity. This hydrogel exhibited excellent biocompatibility and broad-spectrum antibacterial effects against S. aureus and E. coli. Furthermore, it possessed improved mechanical properties and biosafety, demonstrating potential applications in wound healing and tissue engineering[29]. Amir et al. developed a multifunctional hydrogel dressing by crosslinking chitosan and PVA with vanillin and reinforcing the structure using nanocellulose and CuO-Ag nanoparticles, as shown in Fig. 1(d). This dressing exhibited excellent mechanical strength, high hydrophilicity, and controlled swelling behavior, as well as good biodegradability and cytocompatibility. It showed remarkable antibacterial activity against both Gram-positive and Gram-

negative bacteria and effectively promoted wound healing. This innovative hydrogel, integrating nanoreinforcement with biopolymer technology, holds significant clinical potential for wound care[30].

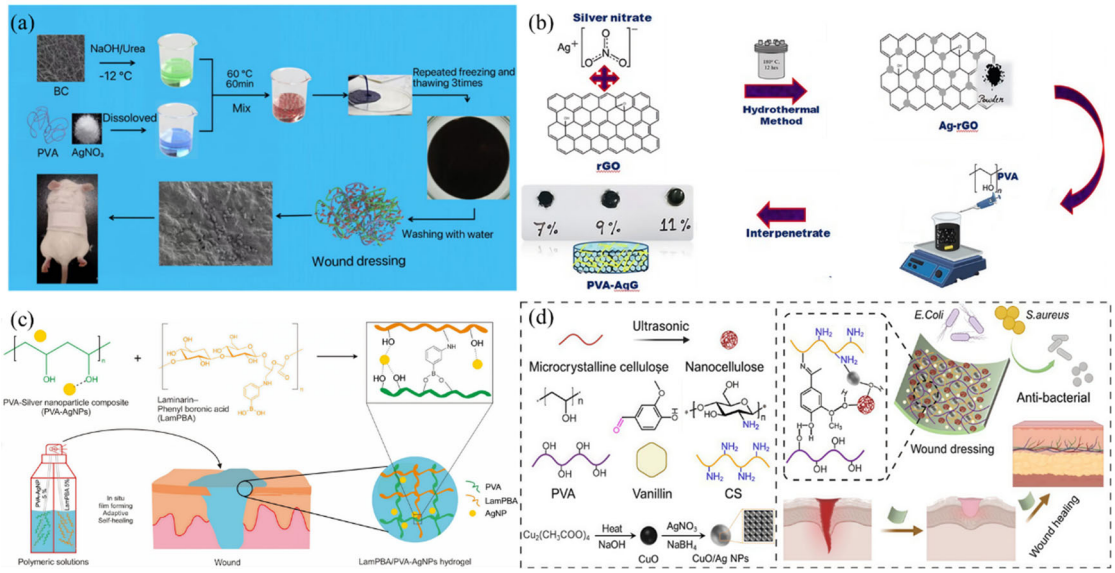

Fig. 1. PVA hydrogels loaded with inorganic antibacterial materials. (a) Preparation of PVA/BC-Ag hydrogels[26]; (b) preparation of PVA-AgG nanocomposite hydrogels[27]; (c) preparation of LamPBA/PVA-AgNPs hydrogels[28]; (d) preparation of multifunctional CuO-Ag-NP-reinforced hydrogel wound dressing[30].

3.2 PVA Hydrogels Loaded with Antibiotics or Antibacterial Active Substances

As a local drug delivery matrix, hydrogels possess high water content and excellent biocompatibility, enabling selective and controlled release of antibiotics and improving drug utilization[31]. Commonly loaded antibiotics include ciprofloxacin (CIP) and amoxicillin (Amox), which can be incorporated into hydrogel matrices via physical encapsulation or chemical bonding to prepare efficient and intelligent antibacterial dressings.

Among them, CIP is a fluoroquinolone broad-spectrum antibacterial agent that exhibits strong inhibitory effects on both Gram-positive and Gram-negative bacteria. CIP can be incorporated into hydrogel networks through self-assembly with tripeptides, forming antibacterial hydrogels with high drug-loading efficiency and sustained-release capability, showing significant antibacterial activity against S. aureus, Klebsiella pneumoniae, and E. coli[32]. Rani et al. used glutaraldehyde (GA) as a crosslinker and synthesized a novel crosslinked hydrogel film based on carboxymethyl tamarind kernel gum, PVA, and guar gum. The material demonstrated excellent mechanical properties and thermal stability. As a drug carrier, the hydrogel film efficiently loaded CIP and exhibited significant antibacterial activity against E. coli and S. aureus, highlighting its potential for biomedical applications such as wound dressings[33]. Amox, a commonly used broad-spectrum antibiotic, kills bacteria by inhibiting bacterial cell wall synthesis and is effective against various Gram-positive and some Gram-negative bacteria. Kiti et al. developed an intelligent wound dressing with bacteria infection visualization capability by incorporating Amox and butterfly pea flower extract (BPE) into PVA-based hydrogels, including PVA/alginate (PVA/Alg) and PVA/carboxymethyl cellulose (PVA/CMC) systems. The dressing exhibited excellent mechanical performance—including enhanced compressibility, hardness, and adhesiveness—along with strong antibacterial activity. Furthermore, due to the pH-responsive characteristics of BPE, the dressing could visually monitor wound infection. In vitro studies confirmed good biocompatibility, supporting dermal fibroblast adhesion and proliferation. This multifunctional dressing integrates therapeutic and diagnostic functions, enabling real-time wound monitoring[34].

To address bacterial resistance caused by antibiotic abuse, the most direct approach is to replace antibiotics with natural active substances, such as polyphenols and essential oils derived from plants. Loading these bioactive molecules into hydrogel networks allows for controlled and sustained release,

while the intrinsic moist environment of hydrogels synergistically enhances antibacterial efficacy. Thus, safe and efficient antibacterial dressings can be developed without reliance on antibiotics. Omoyeni et al. identified the active components of Ricinus communis essential oil and incorporated them into PVA/gum arabic hydrogels prepared via freeze-drying, developing a novel antibacterial gel material based on plant essential oils and biopolymers. The hydrogel demonstrated good antibacterial effects against S. aureus and Bacillus subtilis, as well as excellent moisture retention and breathability, showing potential for wound dressing and biomedical applications as an alternative to traditional antibiotics[35]. Yang et al. used PVA, carboxymethyl cellulose (CMC) containing multiple carboxyl and hydroxyl groups, and polyethylene glycol (PEG) as a pore-forming agent to prepare a novel macroporous PVA/CMC/PEG composite hydrogel via freeze-thaw and phase separation techniques. On this basis, they further prepared PVA/CMC/PEG@ZIF-L composite hydrogel dressings through in situ growth, as shown in Fig. 2(a). This hydrogel dressing exhibited rapid hemostatic ability and enhanced early-stage cell proliferation, significantly improving coagulation efficiency[36].

In addition to plant extracts, peptides are also commonly used antibacterial active substances. Their strong cationic nature enables them to disrupt bacterial cell membranes and exert bactericidal effects. Zhan et al. combined PVA with chitosan loaded with antimicrobial peptide MSI-1 and incorporated Prussian blue nanoparticles to prepare a novel dual-mode antibacterial hydrogel dressing, as shown in Fig. 2(b). This hydrogel effectively killed S. aureus and E. coli while exhibiting near-infrared photothermal responsiveness, enabling mild hyperthermia to inhibit bacterial biofilm formation. Furthermore, the material showed excellent biocompatibility, combining strong antibacterial activity with high safety, providing a more selective dressing option for the treatment of infected skin defects[37]. To enhance the antibacterial activity of incorporated agents, chemical modification methods such as grafting, crosslinking, and copolymerization are often employed. Zhong et al. developed a multifunctional composite hydrogel dressing using a PVA-borax gel matrix, synergistically reinforced by dopamine-grafted oxidized carboxymethyl cellulose (OCMC-DA) and cellulose nanofibers, while introducing neomycin both as an antibacterial agent and crosslinker, as shown in Fig. 2(c). This hydrogel exhibited good stretchability, high purity, non-toxicity, and excellent biocompatibility, showing great potential for biomedical wound-healing applications[38]. Zhang et al. integrated methacrylated quaternized chitosan, PVA, zeolitic imidazolate framework-8 (ZIF-8), and nicotinamide mononucleotide (NMN) to develop a multifunctional photo-crosslinked hydrogel (QMPZN) that achieved synergistic antibacterial and regenerative therapy. The continuous release of Zn^{2+} from ZIF-8 and the quaternary ammonium groups provided dual antibacterial mechanisms, while controlled NMN release promoted cellular metabolism and tissue repair. QMPZN effectively eradicated S. aureus and E. coli infections and accelerated epithelial regeneration and collagen deposition, proposing a novel solution for the treatment of infected wounds[39].

During the preparation of such hydrogels, silk-derived materials such as silk fibroin and sericin are often introduced to enhance the mechanical strength and bioactivity of the hydrogels. Kuchaiyaphum et al. employed dialdehyde starch as a crosslinker to prepare a novel silk fibroin (SF)/PVA hydrogel via photo-crosslinking, as shown in Fig. 2(d). This hydrogel dressing avoided the issue of crosslinker toxicity residues and exhibited high swelling capacity and water vapor permeability, maintaining moisture balance at the wound site. Therefore, it holds broad application prospects in wound dressing fields[21].

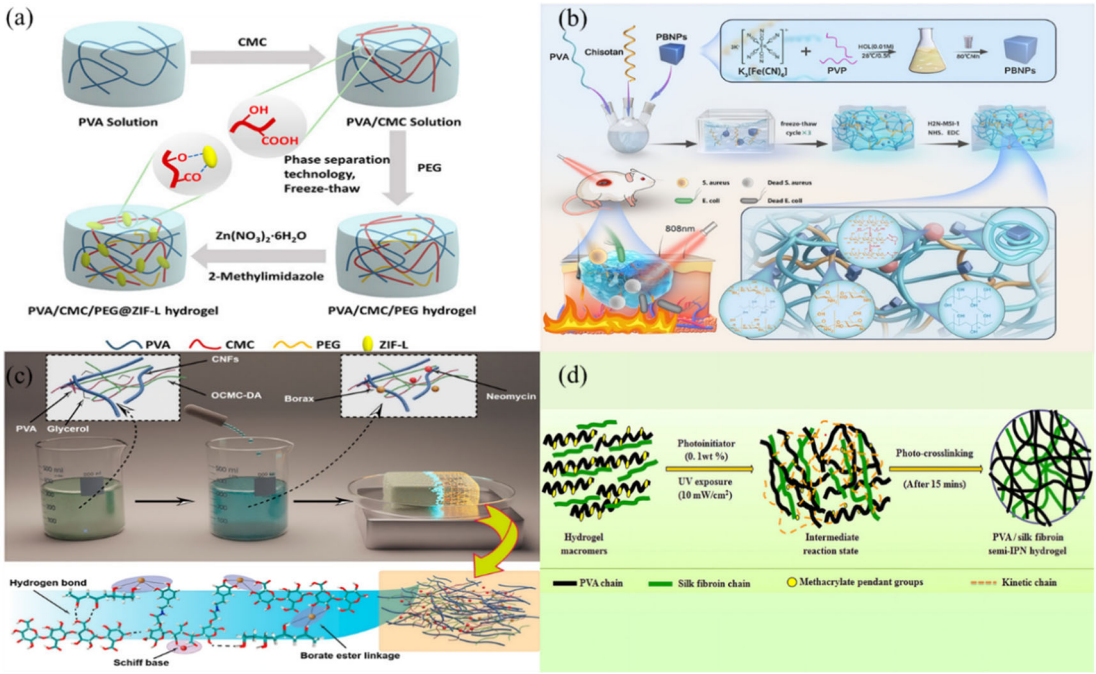

Fig. 2. PVA hydrogels loaded with antibiotics or antibacterial active substances. (a) Preparation of PVA/CMC/PEG@ZIF-L hydrogel[36]; (b) preparation of photothermal nanoparticle/antimicrobial peptide MSI-1/chitosan/PVA hydrogel[37]; (c) preparation and microstructure of OCMC-DA/polyol/borax hydrogel[38]; (d) preparation of silk fibroin/PVA semi-interpenetrating network hydrogel via photo-crosslinking[21].

3.3 PVA Hydrogels with Inherent Antibacterial Ability

Hydrogels with inherent antibacterial ability refer to materials whose antibacterial properties derive from their own chemical structures, either natural or synthetic, without requiring the addition of external antibiotics or antibacterial agents. Consequently, they can achieve long-term and stable antibacterial effects[40],[41]. The antibacterial mechanism of such hydrogels typically involves cationic groups (such as quaternary ammonium salts) that interact electrostatically or through hydrogen bonding with negatively charged bacterial cell walls, adhering to the bacterial surface, increasing membrane permeability, disrupting the membrane, and ultimately leading to bacterial death[42],[43].

Sabrin et al. treated PVA hydrogel films with helium plasma jets and subsequently performed grounding and hydration treatments to promote the electrochemical generation of hydrogen peroxide, thereby enhancing the antibacterial action of plasma-activated hydrogel therapy. The experimental setup is illustrated in Fig. 3(a). The resulting dressing exhibited potent bactericidal activity against E. coli and Pseudomonas aeruginosa, as well as antibacterial effects against S. aureus. This suggests its potential as an alternative to antibiotics and silver-based dressings, offering effective infection control and promoting wound healing[44]. Liu et al. combined PVA hydrogels with standard medical gauze to fabricate a biomimetic moisturizing antibacterial hydrogel dressing (BMAHD). This hydrogel dressing exhibited high breathability and excellent cytocompatibility, while secreting a water-glycerol mixture to maintain wound moisture. Additionally, it released Na_2CO_3 to achieve broad-spectrum antibacterial activity, overcoming common limitations of traditional antibacterial agents such as bacterial resistance and toxicity. As shown in Fig. 3(b), experimental results confirmed that the dressing was non-cytotoxic and effectively promoted wound healing, realizing a synergistic effect of breathability, moisturizing, and antibacterial performance[45].

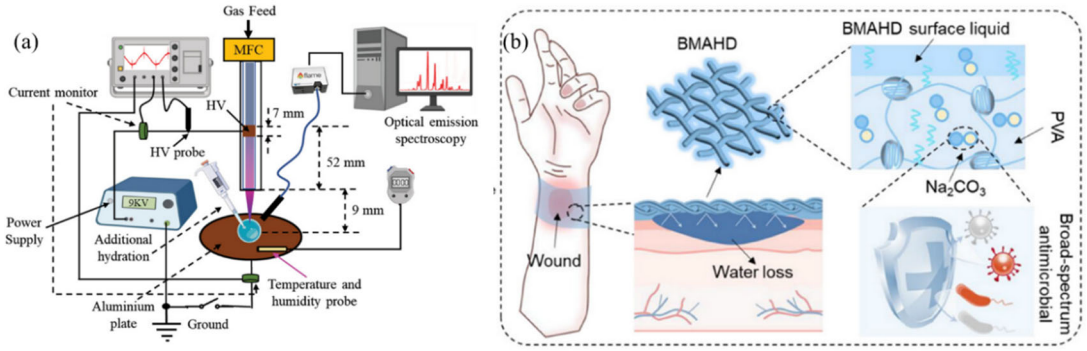

Fig. 3. PVA hydrogels with inherent antibacterial ability. (a) Experimental setup for helium plasma jet activation of PVA hydrogels[44]; (b) schematic of moisturizing and broad-spectrum antibacterial characteristics of BMAHD[45].

4. Conclusions and Outlook

Due to its outstanding mechanical properties, excellent biocompatibility, simple preparation process, biodegradability, and ease of modification, PVA hydrogel has become one of the most widely used materials in the field of antibacterial medical dressings. At present, most PVA hydrogels are loaded with metallic nanoparticles, antibiotics, or antibacterial active substances. These hydrogels can effectively kill bacteria, promote wound healing, reduce the abuse of antibiotics, and minimize the development of bacterial resistance.

However, despite the remarkable progress achieved in PVA hydrogel research, several challenges remain in practical applications, which can be summarized as follows:

(1) The currently common preparation techniques (such as the freeze-thaw method and chemical crosslinking) exhibit distinct limitations. Although the freeze-thaw method is simple to operate, it requires a long preparation period, and the resulting hydrogels often suffer from limited storage stability. In contrast, the chemical crosslinking method can improve mechanical performance but may introduce biological toxicity due to the use of chemical crosslinkers, thereby restricting its biomedical applications.

(2) Under dynamic mechanical environments (such as repeated joint motion), the internal physically crosslinked networks of PVA hydrogels may undergo irreversible damage under cyclic loading, leading to gradual deterioration of mechanical performance. Moreover, their self-healing ability is usually limited, and the recovery rate often fails to meet long-term durability requirements, affecting their sustained functionality in biomedical use.

(3) Although PVA hydrogels generally exhibit good short-term biocompatibility, long-term implantation in vivo may result in the generation of micro-particles due to material wear, potentially triggering chronic inflammation or adverse tissue reactions, thereby posing certain biosafety risks.

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