Journal of Functional Materials and Applied Engineering

Review Paper

Polypyrrole Conductive Hydrogels: Preparation and Recent Advances in Biomedical Applications

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Abstract. Hydrogels are a class of materials characterized by high water content, favorable biocompatibility, and an extracellular matrix (ECM)-like structure. Among them, polypyrrole (PPy) conductive hydrogels integrate the physical properties of conventional hydrogels—such as a three-dimensional porous architecture and high water retention—with excellent electrical conductivity. These materials enable the detection of bioelectrical signals generated by biological systems and provide electrical stimulation to modulate cellular and tissue activities and functions, making them widely applicable in the biomedical field. This review summarizes recent advances in PPy conductive hydrogels for biomedical applications. Based on the cross-linking mechanisms between PPy and the hydrogel matrix, PPy conductive hydrogels are categorized into non-covalently cross-linked and covalently cross-linked types. We focus on their applications in skin wound repair, neural regeneration, myocardial repair, and flexible sensing, and discuss current development trends and existing challenges for PPy conductive hydrogels in biomedicine.

Keywords: *Polypyrrole; Hydrogel; Electrical conductivity; Tissue repair; Flexible sensing*

Received on 02 June 2025, Accepted on 02 August 2025, Published on 15 September 2025

1 Introduction

Hydrogels are three-dimensional polymer network systems formed by hydrophilic polymer chains, exhibiting favorable biocompatibility, biodegradability[1], and ECM-mimicking properties, which have led to their widespread use in biomedicine. Typically, hydrogels are formed via diverse cross-linking mechanisms from polymer chains dispersed in an aqueous medium[2] and can be classified into physically cross-linked and chemically cross-linked types[3]. Chemically cross-linked hydrogels undergo gelation through monomer polymerization triggered by light[4], heat[5], mechanical force[6], or pH changes[7–9], while physically cross-linked hydrogels form via physical interactions such as electrostatic forces[10], ionic interactions[11], hydrogen bonding[12], and chain entanglement[13]. Currently, most biomedical hydrogels exhibit negligible electrical conductivity, limiting the introduction of electrical signals into these systems[14] and restricting their broader biomedical utility. Introducing electrical conductivity enables hydrogels to conduct and detect bioelectrical signals, thereby advancing applications including skin wound healing, neural repair, myocardial regeneration, and flexible sensing.

Since the first report of conductive hydrogels in 1994, significant research has focused on synthesizing conductive hydrogels by incorporating conductive components into traditional hydrogel matrices. Common conductive additives include conductive polymers such as polypyrrole (PPy)[15], polyaniline[16], polythiophene and its derivatives[17], as well as carbon-based nanomaterials like carbon nanotubes[18] and graphene[19]. Among these, PPy stands out as a conductive polymer with exceptional electrical conductivity[20], good biocompatibility[21–22], excellent redox activity[23], and environmental stability[24], demonstrating immense potential for biomedical applications. PPy can modulate cell migration, proliferation, and differentiation, making it well-suited for

composite formation with hydrogels to yield stable PPy conductive hydrogels. The incorporated PPy component typically enhances cell adhesion and growth[25], improves the mechanical properties of the hydrogel matrix, and increases its mechanical strength[26]. Moreover, PPy conductive hydrogels exhibit responsiveness to electrical stimulation, enabling the transmission of electrical signals to electro-sensitive cells (e.g., skin cells, neurons, and muscle cells) to promote their proliferation and differentiation[27]. This property facilitates tissue injury repair and also supports the development of flexible sensors that can be worn on the body surface[28] for human motion monitoring and wireless communication[29].

In recent years, substantial progress has been achieved in the research and application of PPy conductive hydrogels. This article introduces the design and fabrication methods of PPy conductive hydrogels and reviews their recent advances in biomedical fields including skin wound repair, neural repair, myocardial repair, and flexible sensing.

2 Design and Fabrication of PPy Conductive Hydrogels

PPy conductive hydrogels are the most extensively studied class of conductive hydrogels due to their straightforward synthesis, excellent electrical performance, and good biocompatibility. Based on the cross-linking mechanisms between PPy and the hydrogel matrix, they are primarily classified into two categories: non-covalently cross-linked PPy conductive hydrogels and covalently cross-linked PPy conductive hydrogels, with the former being more commonly reported.

2.1 Non-Covalently Cross-Linked PPy Conductive Hydrogels

Non-covalently cross-linked PPy conductive hydrogels are typically fabricated via in situpolymerization or a one-pot method, where the electroactive component PPy and non-conductive components are integrated through non-covalent interactions. In situpolymerization involves introducing pyrrole monomers into a pre-formed hydrogel matrix, followed by polymerization within this matrix to yield the PPy conductive hydrogel. The one-pot method entails mixing pyrrole monomers with monomers of the non-conductive polymer, adding an initiator, and performing simultaneous polymerization to obtain PPy conductive hydrogels with varied matrices.

The in situpolymerization approach enables uniform dispersion of PPy within the hydrogel matrix, ensuring stable and reliable electrical conductivity. This method typically involves first dispersing pyrrole monomers within the hydrogel matrix, followed by immersion in an initiator solution to trigger pyrrole polymerization into PPy. Lo et al.[30] proposed an in situpolymerization method to synthesize PPy within a nanostructured, stretchable, and thermo-responsive poly(N-isopropylacrylamide) (PNIPAAm) hydrogel matrix, yielding a self-sensing actuator. The resulting poly(N-isopropylacrylamide-co-acrylic acid) (P(NIPAAm-co-AA)) nanogel featured an interpenetrating double-network structure comprising the nanostructured thermo-responsive PNIPAAm and the light-absorbing conductive polymer PPy. As illustrated in Fig. 1, a transparent, colorless PNIPAAm hydrogel matrix was first prepared, immersed in a pyrrole solution to allow monomer adsorption, and then incubated in an ammonium persulfate (APS) solution at 50 °C to facilitate in situPPy polymerization within the matrix. The incorporation of black PPy transformed the hydrogel from transparent to black. This design endowed the material with photo-, thermo-, and piezoresistive responsiveness, enabling remote actuation triggering and localized strain sensing.

Chen et al.[31] fabricated a PPy conductive hydrogel using polyvinyl alcohol (PVA) as the backbone, combined with the polymerization and cross-linking of PPy and polyacrylamide (PAAM). Pyrrole monomers were first added to the PVA matrix, followed by APS initiation to induce in situPPy polymerization within the PVA matrix; at this stage, gelation had not yet occurred. Acrylamide was subsequently introduced to finalize the formation of the polyvinyl alcohol-polyacrylamide-PPy (PVA-PAAM-PPy) conductive hydrogel. Multiple hydrogen bonds between the interpenetrating networks of PVA, PPy, and PAAM endowed the conductive hydrogel with outstanding mechanical properties: a tensile strength of 0.2 MPa at 500% elongation and a compressive strength of 1.5 MPa at 90% compression, alongside an electrical conductivity of 0.3 S/m. Thus, this hydrogel is suitable for use as a strain sensor in flexible wearable electronic devices for signal detection.

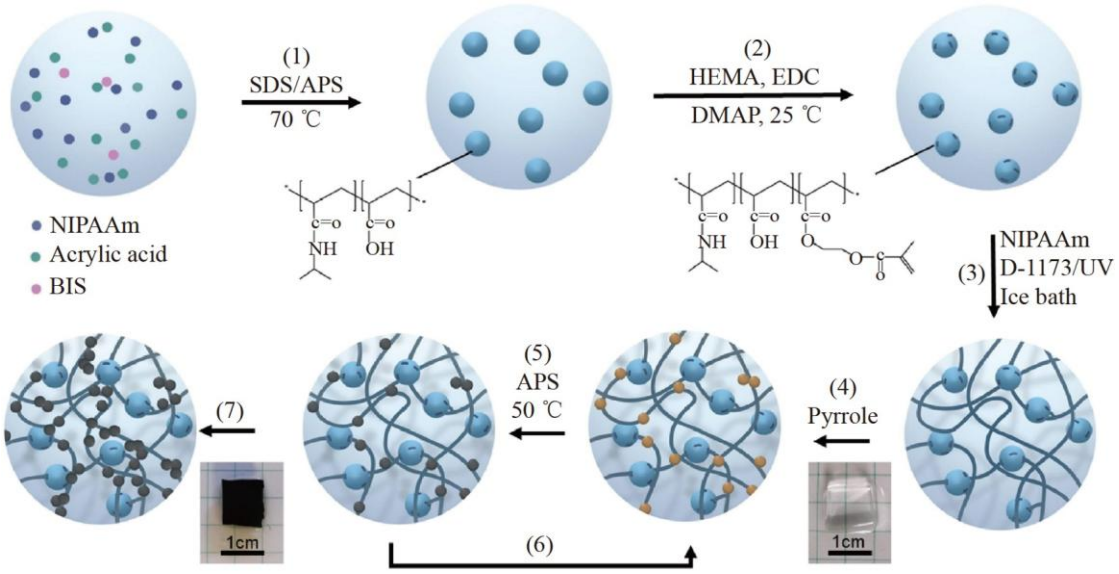

Figure 1 Preparation of poly(N-isopropylacrylamide-co-acrylic acid) (P(NIPAAm-co-AA)) nanogel[30]

Inspired by mussel adhesive structures, our research group employed the catechol derivative dopamine (DA) as both a dopant and a mediator to achieve in situPPy polymerization within a double-network hydrogel matrix, yielding a PPy conductive hydrogel[32]. First, a double-network gelatin methacryloyl-polyacrylamide (GelMA-PAM, denoted GP) hydrogel was fabricated via photocrosslinking; this mild process effectively preserved the microstructure of the hydrogel[33]. The GP hydrogel was then immersed in a pyrrole solution containing DA, allowing pyrrole to adhere to the GP network. Under the action of the dopant DA, pyrrole monomers bound to the GP hydrogel via non-covalent interactions between amino/hydroxyl groups on the hydrogel chains and carbon-oxygen bonds on the pyrrole rings, ensuring uniform dispersion. Finally, the initiator APS was slowly added, and the mixture was stirred at low temperature to facilitate the slow oxidative polymerization of pyrrole into DA-PPy-GP hydrogel. Concurrent with pyrrole polymerization, DA formed oligomers that enhanced the hydrophilicity of PPy chains and further strengthened hydrogen bonding and other interactions between PPy chains and the hydrogel backbone[34]. Conventional methods often result in poor dispersion of conductive polymers within hydrogels. In contrast, the conductive PPy network prepared using DA as a dopant and mediator exhibited exceptional uniformity within the hydrogel, facilitating rapid electron transport. The resulting material demonstrated favorable mechanical properties, biocompatibility, and sensitive strain responsiveness, making it suitable for implantable strain sensing applications.

While in situpolymerization offers advantages, a common limitation arises because the pore size of hydrogels is typically smaller than that of pyrrole monomers, hindering sufficient monomer penetration into the matrix. This often leads to PPy aggregation on the hydrogel surface rather than homogeneous distribution throughout the bulk[35], compromising both electrical and mechanical performance[36]. Wang et al.[37] synthesized a PVA/PPy composite hydrogel via in situPPy polymerization within a PVA matrix; however, the poor dispersion of pyrrole within the PVA matrix resulted in suboptimal electrical conductivity. Notably, the inhomogeneous distribution of PPy is not always detrimental. Kim et al.[38] synthesized a thermo-deformable and thermo-responsive PPy conductive hydrogel film via in situPPy polymerization on a poly(N-isopropylacrylamide) (PNIPAm) matrix. Had PPy penetrated deeply into the PNIPAM bulk, the material would likely have lost its thermo-deformability. To address the issue of uneven pyrrole distribution, the one-pot method—which involves simultaneous polymerization of all monomers—offers a simpler alternative.

The one-pot method is operationally straightforward, involving the simultaneous addition of all required monomers and initiators into a reaction vessel. Wang et al.[39] employed this approach to fabricate a novel multifunctional hydrogel (Fig. 2). Carboxymethyl cellulose, acrylic acid (AA), pyrrole, and Al^{3+} were combined in a single container, followed by addition of the APS initiator to yield a composite carboxymethylcellulose/polyacrylic acid/PPy/aluminum(III) (CMC/PAA/PPy/Al(III)) hydrogel. Multiple dynamic coordination interactions between carboxymethyl cellulose/Al^{3+} and carboxyl groups in polyacrylic acid, coupled

with hydrogen bonding between PPy and hydroxyl/carboxyl groups in carboxymethyl cellulose and polyacrylic acid, endowed the hydrogel with excellent mechanical properties and self-healing capability. Synergistic effects among PPy nanoparticles, free ions, and their interactions conferred good electrical conductivity to the hydrogel.

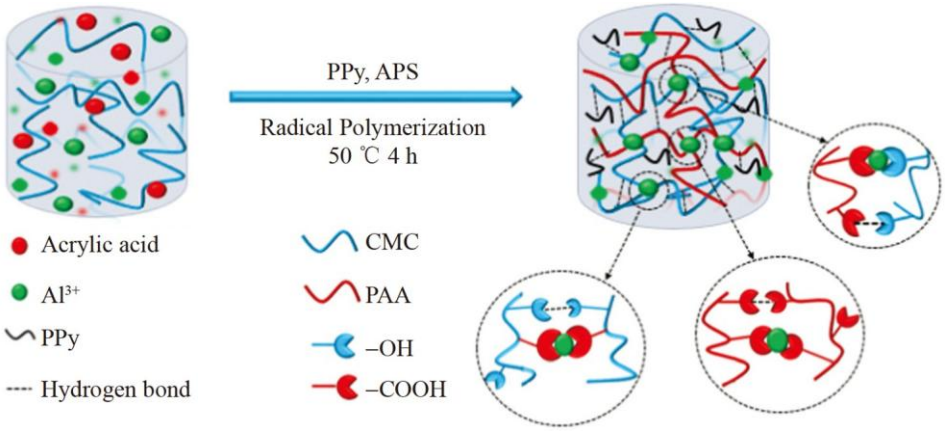

Figure 2 Schematic diagram of preparation of carboxymethylcellulose/polyacrylic acid/polypyrrole/aluminum (CMC/PAA/PPy/Al(Ⅲ)) multifunctional hydrogel[39]

Non-covalently cross-linked PPy conductive hydrogels are synthetically simple. However, because PPy is bound to the hydrogel matrix via non-covalent interactions—which are relatively weak—PPy leakage may occur during practical applications. For instance, when used as tissue repair scaffolds in vivoor in humid environments, or as flexible wearable sensors in underwater or sweat-rich conditions, the swelling nature of hydrogels may cause PPy to leach out under physiological conditions. This not only reduces conductivity but also poses potential cytotoxicity risks[40], compromising performance. Therefore, the design of non-covalently cross-linked PPy conductive hydrogels must account for real-world application requirements to ensure adequate stability, chemical resistance, and mechanical robustness.

2.2 Covalently Cross-Linked PPy Conductive Hydrogels

Covalently cross-linked PPy conductive hydrogels are formed via covalent bonds linking PPy to the hydrogel matrix. The presence of covalent cross-links imparts structural stability, enhanced chemical resistance, and robust mechanical properties[41], offering distinct advantages over non-covalently cross-linked counterparts, which rely on weaker intermolecular interactions.

As illustrated in Fig. 3, Liang et al.[42] designed a paintable conductive hydrogel patch. Pyrrole groups were end-capped onto a dopamine-functionalized hyperbranched polymer, enabling simultaneous in situpolymerization of both pyrrole and DA upon addition of Fe^{3+}. This conductive hydrogel patch exhibited excellent wet adhesion and electrical conductivity. Self-polymerized DA and dopamine-Fe^{3+} coordination complexes provided adhesive properties, while in situformed conductive PPy nanoparticles served dual roles: acting as cross-linking nodes to stabilize the network and imparting electrical conductivity. The synthesis involved a two-step Michael addition reaction to sequentially introduce DA and pyrrole groups, yielding hyperbranched poly(amino ester)-pyrrole (HPAE-Py). A precursor solution was formed by mixing gelatin with purified HPAE-Py polymer, and Fe^{3+} was used to initiate polymerization of the terminal pyrrole groups on HPAE-Py. Additionally, Fe^{3+} acted as a curing agent to form catechol-Fe^{3+} complexes with DA. Covalent tethering of pyrrole groups to water-soluble hyperbranched macromolecules minimized monomer toxicity and leakage. Polymerization occurred in aqueous solution without organic solvents or small molecular additives, ensuring uniform PPy dispersion, which permitted direct in vivoadministration.

Mihic et al.[43] first prepared two PPy-chitosan polymers using PPy/chitosan mass ratios of 3/100 and 3/10, respectively, followed by glutaraldehyde cross-linking to form PPy-chitosan hydrogels (Fig. 4). Hydrogels synthesized from different PPy-chitosan formulations exhibited similar tensile elasticity, suggesting comparable performance when deployed as biomedical materials in dynamic cardiac environments. Cyclic voltammetry

assessments revealed hysteresis loops corresponding to oxidation/reduction states for both PPy-chitosan formulations, whereas unmodified chitosan showed a linear response, confirming the semiconductor behavior of PPy-chitosan hydrogels distinct from pure chitosan.

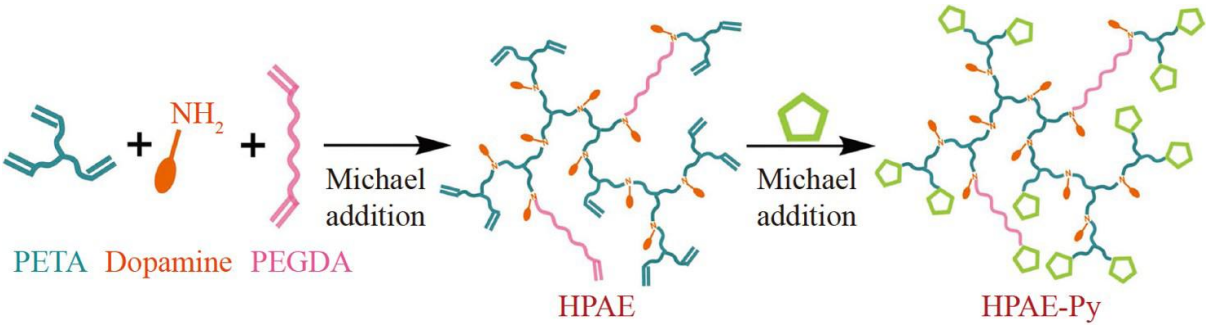

Figure 3 Mechanism of hyperbranched poly(amino)-pyrrole (HPAE-Py)[42]

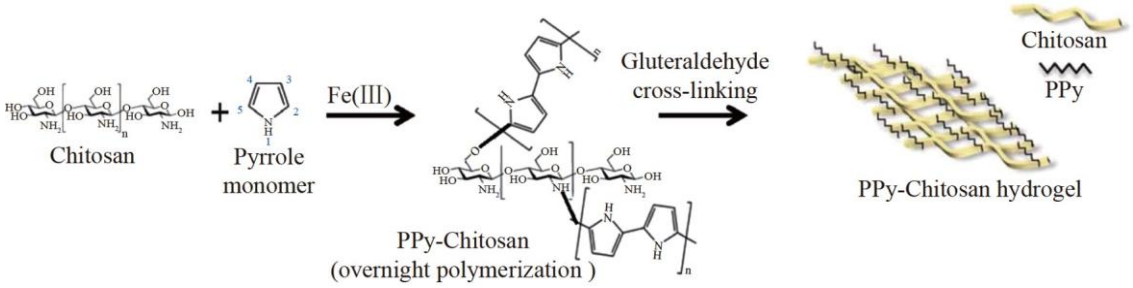

Figure 4 Synthesis of PPy-chitosan hydrogel[43]

Covalent cross-linking expands the possibilities for functionalizing the polymer backbone and side chains with reactive groups, thereby enhancing the chemical versatility of PPy conductive hydrogels. However, covalent cross-linking typically requires monomer modification prior to polymerization, rather than direct use of raw monomers, which may limit practical applicability. While non-covalent cross-linking is synthetically simpler, the weaker interactions involved restrict electrochemical and mechanical performance. In contrast, covalent cross-linking provides structural stability and superior electrochemical and mechanical properties[14], albeit with greater synthetic complexity and controllability challenges. Thus, the design of PPy conductive hydrogels must be purpose-driven, balancing synthetic feasibility with target performance requirements.

3 Applications of PPy Conductive Hydrogels

By integrating the favorable attributes of hydrogels—biocompatibility, three-dimensional porosity, high water content, and ECM-mimicking architecture—with the excellent electrical conductivity of PPy, these composites demonstrate immense potential in biomedical engineering, particularly for skin wound repair, neural regeneration, myocardial repair, and flexible sensing.

3.1 Skin Wound Repair

The skin is the outermost human tissue directly interfacing with the external environment, serving critical functions including sensory perception, thermoregulation, and physical protection against external insults[44]. While most minor skin injuries heal spontaneously, many wounds fail to fully recover functionality[45–46]. Traditional wound dressings (e.g., gauze, bandages, sponges) offer limited functionality, primarily acting as physical barriers and absorbing exudates without actively promoting healing. Furthermore, fibers or debris from these dressings can adhere to the wound bed, causing inflammation and secondary injury upon removal[47]. Hydrogels, with their high water content, favorable swelling behavior, appropriate elasticity, and ECM-like properties, create an optimal microenvironment for wound healing, positioning them as ideal wound dressing

candidates[48]. Conductive hydrogels can further enhance healing by transmitting electrical signals to stimulate skin cells, promoting their proliferation and differentiation.

Feng et al.[49] designed an asymmetric PPy conductive hydrogel with near-infrared (NIR)-triggered tunable adhesion, self-deformation, and antibacterial capabilities. Using pyrrole and DA as precursors, and incorporating N-isopropylacrylamide and AA, they synthesized a PPy-PDA asymmetric hydrogel (Fig. 5). This hydrogel integrated multiple functionalities: NIR-triggered tunable adhesion, self-deformation, and bacterial clearance. Internal water transport enabled self-deformation and adjustable adhesion. As a wound dressing, NIR irradiation facilitated painless, on-demand removal. To evaluate healing efficacy, a rat model of infected skin wounds was established, with groups including: blank control, commercial 3M™ film, hydrogel alone, and hydrogel + NIR irradiation. Wound areas were monitored on days 0, 3, 7, and 16. Only the hydrogel + NIR group achieved complete wound closure by day 16. Masson's trichrome staining on day 16 assessed collagen deposition: both hydrogel-treated groups exhibited uniform collagen bundle deposition, whereas the control and 3M film groups showed clear wound margins with less organized collagen. These results confirmed the excellent wound healing promotion effect of the NIR-irradiated hydrogel group. This multifunctional hydrogel shows promise not only for infected wound management but also provides a new paradigm for designing smart asymmetric hydrogels. Similarly, Wang et al.[50] developed an NIR-responsive PPy conductive hydrogel that demonstrated effective in vitroantibacterial activity via synergistic photothermal and photodynamic therapies. In vivostudies confirmed its ability to control infection and accelerate wound healing. Given that PPy is a dark-colored polymer capable of absorbing NIR light and converting it to heat for photothermal therapy, PPy conductive hydrogels hold great potential for treating infected wounds.

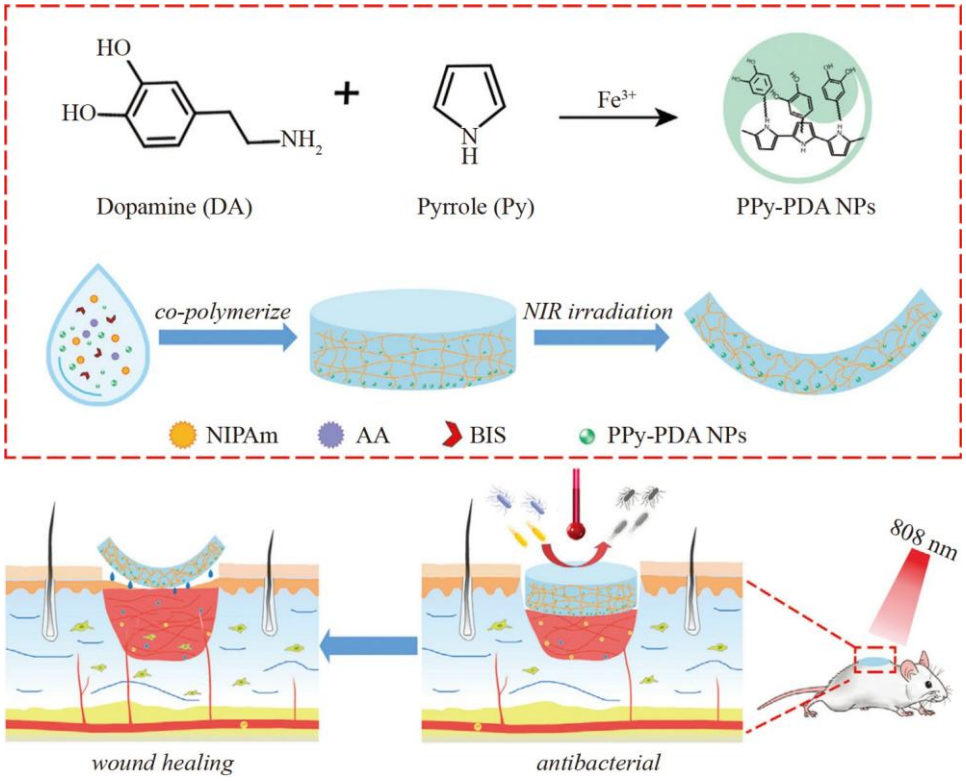

Figure 5 Schematic diagram of manufacturing process and application of asymmetric hydrogel of PPy-polydopamine (PPy-PDA)[49]

Chronic skin wounds pose significant clinical challenges. Combining electrical stimulation (ES) with hydrogel dressings represents a promising therapeutic strategy. Zhang et al.[51] developed a cost-effective, easily fabricated PPy conductive hydrogel with autonomous self-healing capability, using PVA and functionalized chondroitin sulfate (CS) as precursors (denoted PCPZ hydrogel). As a conductive wound dressing, PCPZ was applied to a diabetic rat chronic wound model, with groups including: control, commercial aqueous dressing, PCPZ hydrogel

alone, and PCPZ + ES (3 V). Results showed that the commercial aqueous dressing alone did not accelerate healing; the PCPZ hydrogel group showed moderate improvement; and the PCPZ + ES group exhibited significantly enhanced wound closure, likely by maintaining or amplifying endogenous wound currents. However, this study did not investigate the impact of varying ES voltages on healing outcomes, representing a direction for future research. Beyond promoting cellular responses via conductivity, the integration of ES with conductive hydrogels represents a key advantage over traditional dressings.

3.2 Neural Repair

The central nervous system has limited intrinsic regenerative capacity[52], making neural regeneration a major challenge in biomedical engineering. Neural regeneration is modulated by numerous biological factors, including electrical signals, which regulate adhesion, metabolism, proliferation, migration, and differentiation of electro-sensitive cells[53]—a category that includes neurons[54]. Conductive hydrogels, particularly those incorporating PPy—a benchmark conductive polymer with high conductivity, environmental stability, and low cytotoxicity[55–57]—show great promise for neural tissue engineering.

Xu et al.[58] developed an injectable PPy conductive hydrogel for neural repair (Fig. 6). This material exhibited high water absorbency and good self-healing properties, promoting the adhesion, proliferation, and differentiation of neural stem cells (NSCs). In a zebrafish brain injury model, injection of CDD hydrogel loaded with NSCs resulted in an 80% survival rate at 6 days post-injury, compared to ~40% for the hydrogel-only group and 30% for the PBS control group. Motor function recovery tests showed that NSC-loaded CDD hydrogel restored 66% and 80% of locomotor activity at 4 and 6 days, respectively, outperforming the hydrogel-only group (47% and 53%) and the control group (21% at 6 days). These findings highlight the material's potential for neural repair and motion sensing. Our research group designed a porous, highly conductive, flexible, and adhesive PPy conductive hydrogel film with good biocompatibility[59]. This thin-film dressing could readily adhere to nerve fibers and spontaneously form tubular structures, simplifying the clinical procedure for treating peripheral nerve injury (PNI) in diabetic patients. Beyond promoting axonal extension in vitro, the hydrogel enhanced Schwann cell adhesion and migration. In vivostudies in diabetic rats confirmed promoted axonal and myelin sheath regeneration. Additionally, the hydrogel facilitated nerve impulse conduction and muscle sensation, preventing denervation atrophy and preserving muscle function.

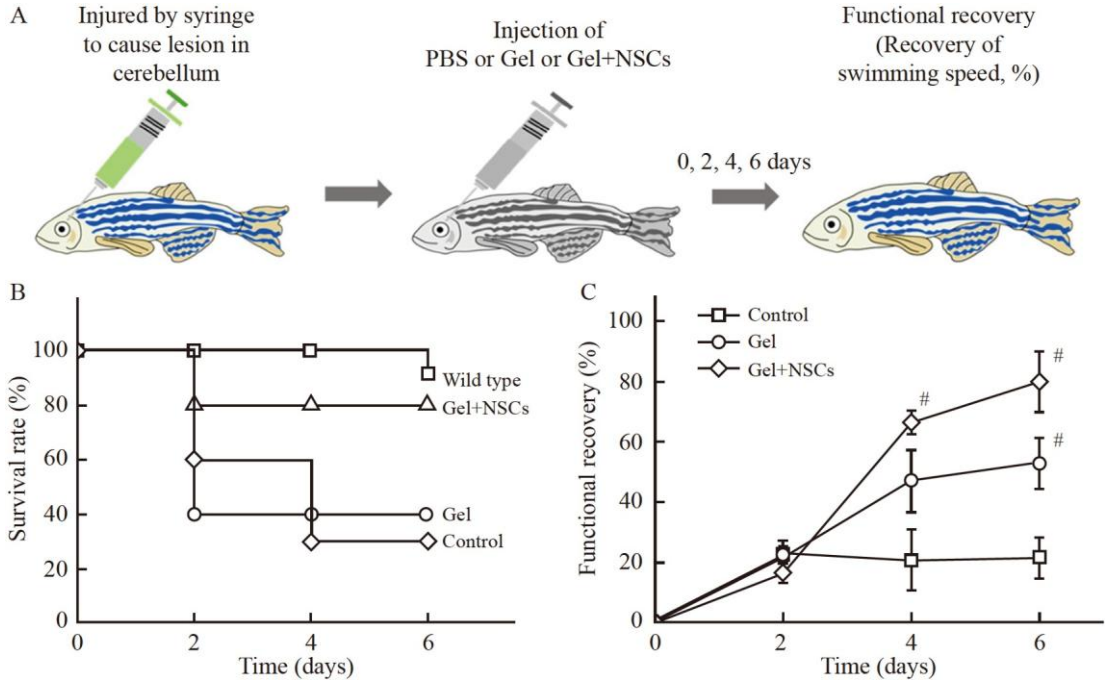

Figure 6 Nitrogen-carboxyethyl chitosan, chitosan-modified PPy, polyurethane (CDD) hydrogels used to repair and treat central nervous system injury in adult zebrafish, and treatment includes injection of

PBS (control group), CDD hydrogels alone (Gel), and CDD hydrogels loaded with neural stem cell (NSC) (Gel+NSCs): (A) Mapping of nerve damage and motor function in adult zebrafish; (B) Survival rate of zebrafish with brain injury; (C) Exercise recovery monitoring of experimental zebrafish for a period of 6 d (n=11, #: $p<0.05$)[58]

Native neural tissue comprises aligned fascicles, where matrix conductivity supports intercellular signaling and external electrical stimulation delivery. Wu et al.[60] adopted a biomimetic strategy inspired by the neural ECM, synthesizing hydrophilic conductive PPy nanoparticles to improve dispersion within collagen hydrogels. Using microfluidics, they fabricated cell-laden PPy-collagen hydrogel microfibers with highly oriented microstructures. These microfibers mimicked the native ECM, providing cell-adhesive, aligned fibrous architectures with inherent conductivity. The aligned structure promoted neurite outgrowth and enhanced axonal alignment, while matrix conductivity upregulated neuronal gene expression. External electrical stimulation further amplified neuronal maturation. Reverse transcription polymerase chain reaction (RT-PCR) analysis assessed the impact of ES on neurogenesis-related gene expression in PC12 cells. Without ES, all groups showed slight upregulation of β3-tubulin (a neuronal marker). Following three rounds of ES, β3-tubulin expression increased 2.2-fold in the collagen-rich hydrogel group, confirming the synergistic effect of ES and the biomimetic hydrogel microenvironment. This approach offers a powerful platform for constructing neural regeneration niches. Collectively, the favorable biocompatibility and high conductivity of PPy conductive hydrogels position them as promising candidates for promoting neural regeneration after injury.

3.3 Myocardial Repair

Myocardial infarction (MI) remains a leading cause of global mortality, driving the development of therapeutic materials and techniques such as bioinjectables and cardiac patches to restore infarcted myocardium function[61]. However, invasive approaches—including intracavitary delivery, sutured patches, and catheter-based injections—risk secondary damage to fragile myocardial tissue[62]. PPy conductive hydrogels offer a gentler alternative, avoiding iatrogenic injury while leveraging conductivity to support myocardial repair.

Wu et al.[63] proposed a combinatorial therapeutic strategy employing both a conductive hydrogel patch and an injectable hydrogel within infarcted myocardium (Fig. 7). First, a self-adhesive conductive hydrogel patch was fabricated via Fe^{3+}-mediated ionic coordination between gelatin-dopamine (GELDA) and dopamine-functionalized PPy (DA-PPy). Simultaneously, an injectable, degradable hydrogel was formed in situvia Schiff base reactions between oxidized hyaluronic acid (HA-CHO) and hydrazide-modified hyaluronic acid (HHA). Compared to single-material interventions, the combination therapy—intramyocardial injection of HACHO/HHA hydrogel followed by epicardial application of the GELDA/DA-PPy conductive patch—significantly improved cardiac function, as evidenced by echocardiography, histological analysis, and angiogenesis assessments.

Parchehbaf-Kashani et al.[64] successfully developed a PPy-incorporated conductive cardiac scaffold mimicking the cardiac ECM (termed CG-PPy). Cross-linkers were used to enhance mechanical properties. The CG-PPy scaffold provided a biocompatible microenvironment that enhanced the viability, adhesion, and migration of cardiac progenitor cells (CPCs) over 14 days. In vivostudies in MI rats demonstrated that CPC-seeded, cross-linked CG-PPy scaffolds positively impacted cardiac functional recovery. Four weeks post-implantation, the scaffold maintained proliferative and differentiative support for cells, increased the density of α-smooth muscle actin (α-SMA)-positive vascular-like structures, and reduced $CD68^+$ inflammatory cell infiltration, highlighting its clinical potential for post-infarction recovery.

Myocardial injury and disease disrupt electrical signal propagation. Given the limited regenerative capacity of cardiomyocytes, untreated MI leads to permanent fibrotic scarring. PPy conductive hydrogels provide a biocompatible microenvironment that enhances electrical coupling and promotes cardiomyocyte proliferation and differentiation, showing great promise for myocardial repair. However, a key safety concern persists: PPy itself is non-degradable[65]. When used in vivo, degradation of the hydrogel's hydrophilic polymer matrix exposes PPy directly to host tissues. Long-term PPy retention may trigger chronic inflammation[14], necessitating future research into strategies for mitigating this risk.

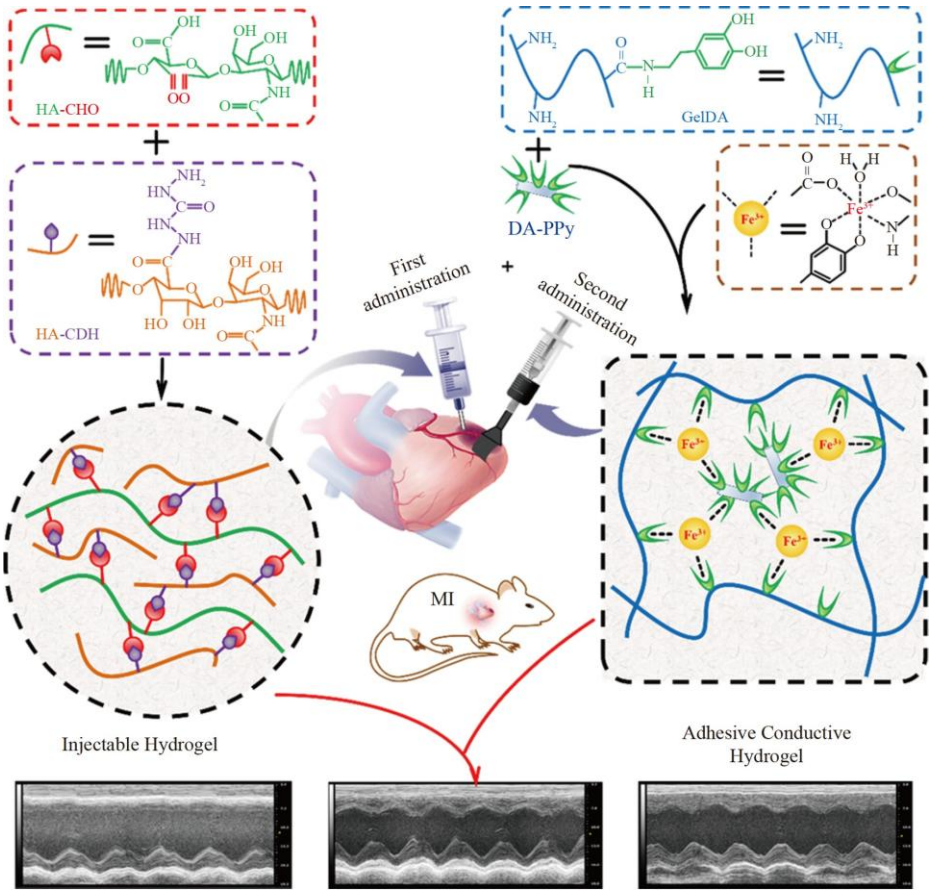

Figure 7 Combination of adhesive hydrogel patch and injectable hydrogel to treat myocardial infarction[63]

3.4 Flexible Sensing

Flexible wearable sensors have garnered significant attention for their utility in motion monitoring[66], health tracking[67], and human-machine interfaces[68–69–70]. Strain sensors conform to deformable substrates; when the substrate deforms, the sensor undergoes concurrent strain, transducing mechanical deformation into measurable electrical signals (e.g., voltage, resistance changes)[71]. Among sensing materials, PPy conductive hydrogels uniquely combine the inherent properties of hydrogels with the electrical conductivity of conventional conductors, offering distinct advantages for flexible sensor design.

Han et al.[72] fabricated a transparent, conductive, stretchable, and adhesive hydrogel by in situforming polydopamine-doped PPy (PDA-PPy) nanofibers within a hydrophilic polyacrylamide network (Fig. 8). The PDA-PPy nanofibers integrated seamlessly into the hydrogel network, establishing continuous conductive pathways. Catechol groups on PDA-PPy nanofibers conferred strong tissue adhesion, while increasing nanofiber content enhanced toughness and stretchability. This strategy of in situconductive nanofiber formation offers a facile route to incorporate otherwise insoluble, hydrophobic conductive polymers into hydrogels, yielding multifunctional materials suitable for sensors, transparent electronic skin, and biocompatible bioelectrodes. Li et al.[73] designed a multifunctional PPy conductive hydrogel using sodium alginate, dopamine-functionalized PPy, and borax. With a high conductivity of (1.33 ± 0.012) S/m, the hydrogel functioned as a strain sensor with a gauge factor of 10.23, delivering stable, repeatable responses capable of ultrasensitive monitoring ranging from large joint motions to subtle muscle movements.

Despite their promise, a critical challenge remains: water plasticization can degrade hydrogel performance, complicating the design of biosafe sensors for underwater or humid environments. Zheng et al.[74] addressed this by constructing a SF/TA@PPy conductive hydrogel via in situpolymerization, incorporating silk fibroin (SF) and

tannic acid (TA) into the PPy network. The resulting hydrogel exhibited excellent extensibility, skin conformity, antimicrobial activity, and biocompatibility, alongside robust self-healing capability in both air and water. Even in moist conditions, SF/TA@PPy maintained strong adhesion to diverse substrates. It offered a wide working range, high strain sensitivity, and rapid, stable resistive responses over prolonged stretching cycles. As a wearable strain sensor, SF/TA@PPy adhered directly to human skin without auxiliary adhesives, reliably detecting both large-scale motions (finger, wrist, elbow, knee bending) and subtle physiological signals (smiling, frowning, coughing, respiration) in both aerial and aquatic environments. Leveraging its stable electrical properties, the hydrogel enabled Morse code transmission via controlled body movements, facilitating underwater communication. The biocompatibility and antimicrobial properties of PPy-based hydrogels further minimize allergic risks during prolonged skin contact, opening new avenues for physiological signal monitoring in challenging environments.

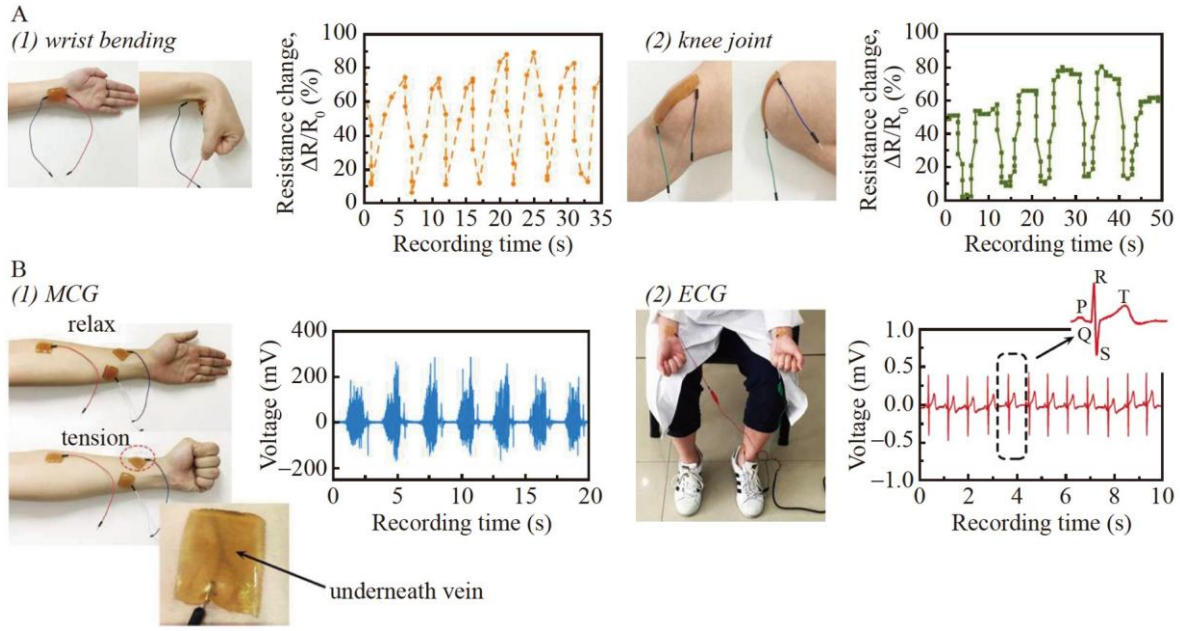

Figure 8 Fig.8 Conductive, adhesive, stretchable and biocompatible polydopamine-polypyrrole-polyacrylamide (PDAPPy- PAM) hydrogel for wearable devices: (A) Hydrogels are attached to (1) wrist and (2) knee joints to act as strain sensors to detect human movement; (B) Hydrogels are used as self-adhesive electrodes to detect (1) electromyographic and (2) ECG signals[72]

4 Conclusion

PPy conductive hydrogels represent a unique class of materials that synergistically combine the advantages of hydrogels and organic conductors. The PPy component establishes efficient interfaces between electronic (electrode) and ionic (electrolyte) transport phases, significantly enhancing charge carrier mobility and stimulus responsiveness. Composite PPy conductive hydrogels based on polymer networks exhibit favorable integrity, strength, elasticity, and mechanical robustness, demonstrating broad application prospects in skin wound repair, neural regeneration, myocardial repair, and flexible sensing. However, several challenges remain:

(1) While PPy generally exhibits good in vitrobiocompatibility in cytocompatibility assays, discrepancies exist between in vitroand in vivooutcomes. In vivo, degradation of the hydrophilic polymer matrix exposes non-degradable PPy directly to host tissues, potentially eliciting adverse long-term responses.

(2) The potential for chronic inflammation upon implantation requires thorough investigation.

(3) For flexible sensing applications, maintaining long-term electrical stability under cyclic deformation and environmental exposure remains a hurdle.

Future research must prioritize addressing these safety and stability concerns to translate promising PPy conductive hydrogel formulations into clinical and commercial reality. This will be the central focus of ongoing and future development efforts in this field.

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