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Review Article

Exploring conductive polymers in biomaterials for electroactive wound dressings and controlled drug release

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A B S T R A C T

Conductive polymers possess electrical conductivities similar to those of human skin, as well as antioxidant and antibacterial activities, and can facilitate the various mechanisms of wound healing through electrical stimulation and targeted drug delivery. This technology can also enable monitoring of wounds in real time and therapeutic responses to the developing wound. This review highlights how using conductive polymers with biomaterials can pave the way for electroactive wound dressings and systems for controlled drug release. We will review the types of conductive polymers, the mechanisms behind their healing and drug delivery, and future directions for research.

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1. Introduction

Associating conductor polymers into biomaterials is an important innovation in the medical field, specifically in wound healing and drug delivery [1, 2]. Conductive polymers (polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT)) are able to conduct electricity, thus they are able to functionally interact with biological tissues and communicate electrical signals to cells [3,4]. This could be used to stimulate cellular activity, enhance tissue repair, and allow continuous healing assessment [5]. The ability to generate, or transmit, bioelectrical signals at the wound site enhances fibroblast migration, collagen deposition, and angiogenesis, which are all important functions for proper wound healing [5, 6]. These electrical capabilities open new pathways for the development of smart biomaterials that not only take part in healing, but also respond to physiological stimuli [1, 7-9]. Additionally, conductive polymers are being used to create controlled drug delivery systems that give the potential for accurate, on-demand therapeutic delivery [10, 11]. These materials can be tailored to release as a function of external electrical signals, allowing for spatial and temporal control over dosage delivery and reduced side effects [12, 13]. This level of dosage delivery has added advantage in the treatment of chronic wounds and localized infections, whose effectiveness could be improved with personalized therapy [12]. Enabling external control of dosage is a major advantage; there are significant challenges to overcome regarding the mechanical properties, biocompatibility, and durability of conductive polymer biomaterials [14, 15]. This review will examine the advances that have been made with conductive polymers as biomaterials, specifically the application of conductive polymers in electroactive dressings and controlled drug delivery. This review investigates the current state of conductive polymers in biomaterials, emphasizing their use in electroactive wound dressings and controlled drug delivery. It underscores key material characteristics, biological interactions, and the challenges and future opportunities in this quickly advancing field.

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2. Conductive Polymers: An Overview

Conductive polymers are a type of organic polymers that can conduct electricity, combining the mechanical traits of plastics with electrical conductivity usually linked to metals or semiconductors [16-18]. This special feature comes from their molecular structure, especially the presence of conjugated double bonds along their backbone, which enables the delocalization of π-electrons and helps facilitate charge transport [19].

2.1. Types of Conductive Polymers

Conductive polymers can be categorized according to their molecular structure, conduction mechanism, and applications. Fig. 1 and Table 1 illustrated the primary types.

2.2. Mechanisms of Electrical Conductivity

Electrical conductivity in materials mainly results from the movement of charge carriers, such as electrons or ions, depending on the material [36]. In metals, free electrons near the Fermi level are responsible, as they can move easily through the crystal lattice. These electrons are loosely bound to atoms and can flow freely under an electric field, leading to high conductivity [37]. Band theory explains this by showing how electrons occupy energy bands; in metals, partially filled bands near the Fermi level provide numerous states for electrons to jump between, enabling conduction [38]. Conversely, insulators and semiconductors have filled bands separated by energy gaps, which restrict electron mobility and lower conductivity [39]. Electrical conductivity involves electron and ionic conduction, with ions in materials like rocks and electrolytes acting as charge carriers [40]. It depends on charge carriers' number, charge, and mobility. Factors such as lattice vibrations and impurities affect conductivity by scattering carriers [41]. At microscopic levels, quantum effects influence charge movement, especially in nanoscale materials, impacting high-tech devices [42, 43]. Overall, it is determined by the material's atomic structure, charge carrier presence and mobility, and external factors like temperature and impurities [36, 44].

2.3. Biocompatibility and Degradability

Conductive polymers are increasingly seen as promising materials for biomedical uses because they uniquely combine electrical conductivity with potential biocompatibility [45, 46]. However, traditional intrinsically conducting polymers (ICPs) such as PEDOT, PPy, and PANI often have low or no biodegradability, limiting their application in temporary implants or tissue engineering scaffolds where material resorption is necessary [22, 47]. To overcome this, recent developments focus on designing polymers that are both biodegradable and biocompatible [48]. Methods include doping with biodopants or chemically modifying monomers to improve cellular compatibility, as well as creating block copolymers by linking electroactive oligomers with degradable ester bonds or copolymerizing conductive monomers with biodegradable polyesters such as poly(lactic acid) (PLA) or polycaprolactone (PCL). These strategies aim to refine the polymers' chemical and physical features to support cell growth while allowing controlled degradation in body environments [49].

Enhancing the degradability of conductive polymers, such as PEDOT with hydrolyzable side chains, allows for their gradual breakdown under physiological conditions [50]. These bioerodible polymers disintegrate into fragments suitable for renal clearance, reducing toxicity. Their erosion is pH-dependent and can be tailored for a specific lifetime, making them ideal for transient biomedical devices, such as implanted rechargeable batteries [2, 50]. Studies verify their cytocompatibility with various cell types, supporting safe biological integration. Overall, merging electrical functionality with biodegradability and biocompatibility promotes smart biomaterials for tissue engineering, biosensing, and implants [51].

3. Conductive Polymers for Electroactive Wound Dressings and Drug Delivery

Conductive polymers have emerged as a groundbreaking class of materials in biomedical fields, particularly for electroactive wound dressings and controlled drug delivery systems. Their unique combination of electrical conductivity, biocompatibility, and tunable properties makes them ideal for developing advanced biomaterials that can respond to physiological signals and external stimuli [2, 52].

3.1. Mechanisms of Action in Wound Healing

Conductive polymers have electrical conductivity similar to human skin, enabling them to deliver electrical stimulation directly at the wound site [53, 54]. It has been shown that electrical stimulation can accelerate wound healing by stimulating cellular actions such as fibroblast attachment, spreading, proliferation, migration, and angiogenesis [55]. An example of this is the use of PPy-based composite films, especially with electrical stimulation, will modulate cytokines IL-6 and IL-8, as well as growth factors. FGF-1 and FGF-2 are important for supporting tissue regeneration and for myofibroblast transdifferentiation; in human skin wounds, chemicals such as IL-8 and FGF-2 are important [56].

Conductive polymers provide more than just electrical means; they also support wound healing through the production of a microenvironment to support cellular behavior necessary for repair. They maintain a moist, three-dimensional environment that promotes cell migration and growth, which is essential for reepithelialization and extracellular matrix reconstruction [57]. In addition, conductive polymers can be designed to release drugs in response to electrical stimuli providing them with additional therapeutic implications for wound care. Incorporating bioactive molecules and doping agents into conductive polymers can improve biocompatibility, cellular adhesion, and growth, while their antioxidant properties help neutralize reactive oxygen species (ROS), protecting tissues from oxidative damage and infection during healing [58]. Research shows that conductive hydrogels made from CPs like PANI combined with biopolymers such as chitosan not only distribute electrical currents evenly but also function as drug delivery systems, releasing therapeutic compounds like vitamin D to speed up recovery [58, 59]. The combined benefits of electrical stimulation, antioxidant effects, antimicrobial activity, and controlled drug release position conductive polymers as a versatile, multifunctional platform for advanced wound dressings and skin tissue engineering [22, 60]. Moreover, applying electrical stimulation along with conductive polymers has shown to enhance cellular responses and gene activity related to wound healing [8]. Fig. 2. shows schematic illustration of conductive polymers in wound healing and skin tissue engineering, illustrating their various structural forms (films, hydrogels, nanofibers, and scaffolds [61, 62]), and diverse applications including electroactive wound dressings and tissue scaffolds for enhanced healing and regeneration [56].

3.2. Integration of Conductive Polymers in Drug Release

Integrating conductive polymers into drug delivery systems offers a promising method for achieving controlled and targeted drug release [10, 63, 64].

Table 1. Summary Table of Common Conductive Polymers

Polymer Type	Examples	Characteristics & Applications	References
Intrinsically Conductive	Polyaniline, Polypyrrole, Polythiophene, PEDOT:PSS, Polyacetylene	Conjugated polymers, doped for conductivity, used in sensors, electronics, energy devices	[20-24]
Composite Conductive	Polymer + Carbon black, metals	Conductivity via fillers, good mechanical stability	[25-30]
Ionically Conductive	Polymer electrolytes	Ion conduction, used in batteries, fuel cells	[31, 32]
Charge Transfer Polymers	Doped poly(vinyl carbazole), triarylamine doped polymers	Charge transfer mechanism, xerography applications	[33, 34]

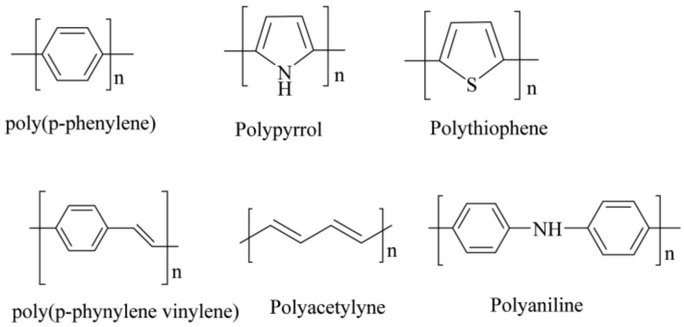

Fig. 1. Structural illustration of some Intrinsically conducting polymers [35].

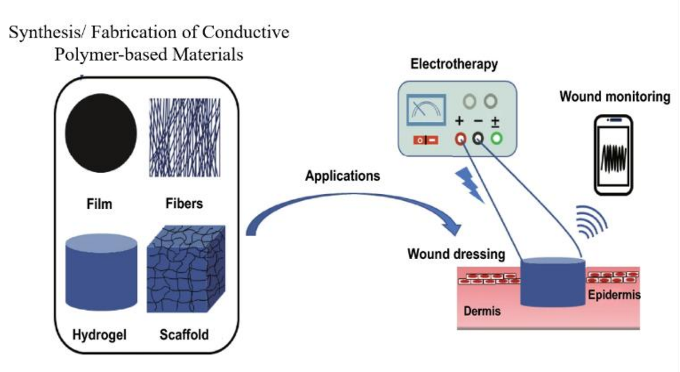

Fig. 2. Schematic depicting conductive polymers for wound healing and skin tissue engineering, showcasing various structural formats and practical applications [56].

Conductive polymers like polypyrrole, polyaniline, and polythiophene derivatives have distinctive electrical properties that allow them to respond to external stimuli, such as electrical fields [1, 65], which can be utilized to control the release of therapeutic agents [66]. When an electrical stimulus is applied, the conductive polymer undergoes redox reactions that induce changes in its structure and porosity. These changes promote controlled release of encapsulated drugs, allowing for on-demand and/or pulsatile drug delivery [67]. This can potentially reduce side effects and increase overall treatment success [68].

4. Future Directions and Challenges

The future directions and challenges of conductive polymers in electroactive wound dressings and controlled drug release place an emphasis on enhancing their multifunctional capacity while providing solutions to several technical and biological challenges [69]. Although conductive polymers provide benefits, a major challenge continues to be controlling drug delivery [70, 71]. For example, single-layer polypyrrole polymers have demonstrated controlled delivery with negligible burst and passive diffusion, but bilayer systems still suffer from burst release as well as unintended polymer residues released. This necessitates further material development and comprehension of drug-polymer interactions to ensure safety and efficacy.

Another key strategy consists of using combination of conductive polymers and non-conductive materials to create composite electroactive dressings for soft tissues whose electrical behaviors resemble human skin, and also deliver an antibacterial and antioxidant property [56]. The combination of electrical stimulation along with conductive polymers has been shown to enhance cellular response and gene response for wound healing, which illustrates the potential to merge materials science with bioelectrical therapies [8].

Furthermore, future research efforts should also aim to develop intelligent wound dressings capable of delivering controlled drug release and providing real-time monitoring of the healing process [72]. Progress in biosensing technologies coupled with conductive polymers will be required to achieve this goal [8]. Moreover, it will be essential to overcome hurdles, such as ensuring long-term biocompatibility, preventing cytotoxicity from breakdown products of the polymer, and adapting manufacturing approaches to mass-scale production[52].

5. Conclusion

To conclude, the incorporation of conductive polymers into biomaterials is a highly promising path toward the development of electroactive wound dressings and systems with targeted controlled drug release. Conductive polymers can conduct electricity in a similar manner to human skin and have a good level of biocompatibility, anti-bacterial and anti-oxidation properties, which collectively can lead to advanced wound healing due to stimulation of electrogenic cells and site-directed drug delivery. Developments in fabrication techniques such as electrospinning offer high levels of control over the physical properties and drug release response profiles of these dressings, reducing the potential for burst release and other issues that can result in systemic toxicity. While challenges remain with respect to drug delivery profiles and biocompatibility of the components in biologically responsive, biomaterials, ongoing explorations of single and bilayer conductive polymer-based systems and composite materials will improve the therapeutic benefits of conductive polymers. Smart bandages that contain conductive polymers offer exciting potential for personalized and on-demand treatments of large chronic and complex wounds while continuing to advance engineering strategies to leverage critical components of tissue engineering and regenerative medicine.

Author Contributions

Mohammad Emami: Conceptualization, Writing – original draft, Writing – review & editing; **Elham Barati:** Writing – original draft, Writing – review & editing. All authors read and approved the final version of manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data is available.

Ethical issues

The authors confirm full adherence to all ethical guidelines, including the prevention of plagiarism, data fabrication, and double publication.

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