

# Biomedical Conductive Polymer: Characteristics and Applications

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## ABSTRACT

Conductive polymers are functional materials that have attracted increasing attention in biomedical applications owing to their ability to combine electrical properties, mechanical flexibility, and biocompatibility. Their  $\pi$ -conjugated electronic structure enables stable electrical conduction, while doping, chemical modification, and composite formation can improve their performance in physiological environments. Conductive polymers have been utilized in various medical technologies, including biosensors, neural interfaces, electrically controlled drug delivery systems, scaffolds for tissue engineering, wearable devices, and flexible bioelectronics. However, several challenges remain, such as long-term stability, brittle mechanical properties, and degradation under biological conditions of use. Further research on elastomeric materials, self-healing systems, and high-conductivity composites is expected to expand their potential applications in modern healthcare technologies. Overall, conductive polymers offer great prospects as innovative materials for next-generation biomedical devices.

**Keywords:** Conductive Polymers, Functional Materials, Biomedical Applications

## I. INTRODUCTION

Conductive polymers are unique materials that combine the electrical properties of organic materials with their beneficial properties. Conductive polymers offer high flexibility and processability, enabling their development as modern functional materials. Conductive polymers can conduct electricity at controllable levels through doping, chemical modification, or structural engineering. The electrical conductivity, biocompatibility, and ease of

functionalization of conductive polymers can be tailored to suit specific applications. This allows for tailoring the material performance to suit application needs, such as the electrical stimulation of neural tissue or measurement of low-intensity biological signals [1,2]. Conductive polymers can be modified to enhance biocompatibility, making them safe for direct contact with body tissues. Unlike metals or inorganic materials, conductive polymers have high flexibility and mechanical properties that mimic soft tissues [3]. This is crucial for the fabrication of bioelectronic

devices attached to mobile organs or used as long-term implants. The combination of conductive polymers with hydrogels, nanomaterials, and biomolecules further expands their potential applications in medicine [4].

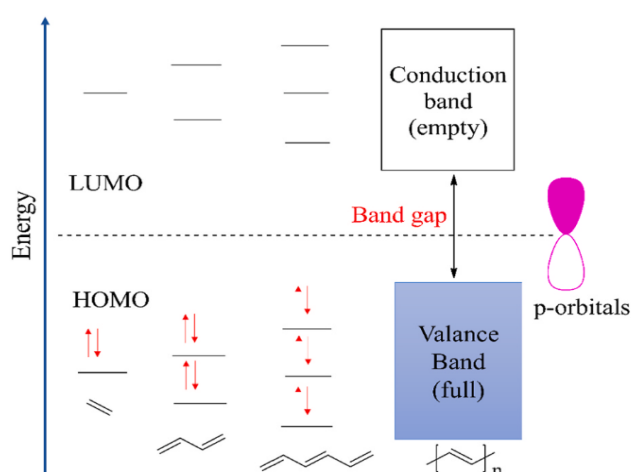
Conductive polymers have the potential for multifunctional applications, serving as both structural components and active elements in various devices. This capability enables the design of lighter, simpler, and more efficient bioelectronic devices. Although conductive polymers show great potential in biomedical and bioelectronic applications, several research gaps remain to be addressed to promote their optimal utilization. To date, many studies have focused on improving the conductivity and biocompatibility of CPs; however, a thorough understanding of the long-term interactions between conductive polymers and biological tissues remains limited. The stability of materials in physiological environments, particularly with regard to degradation, release of chemical residues, and changes in conductive performance over time, has not been comprehensively mapped [5]. Furthermore, most research is still conducted at the laboratory scale under controlled in vitro conditions, thus facing significant uncertainty in its translation to in vivo or clinical applications [6].

The primary objective of this review is to provide a comprehensive overview of the latest developments in conductive polymers and their potential applications in the biomedical field. This review identifies key material characteristics that support performance, evaluates advances in the design and modification of conductive polymers to improve biocompatibility, stability, and integration with biological tissues, and presents a critical analysis of the technical and biological challenges that limit their clinical implementation. Furthermore, this review outlines existing research gaps and provides prospective insights into future research directions and opportunities, serving as a strategic reference for

researchers in developing innovative conductive polymer-based bioelectronic materials and devices.

## II. ELECTRONIC STRUCTURE AND CONDUCTIVITY MECHANISM

Conductive polymers can conduct electricity owing to the presence of a  $\pi$ -conjugated system in their polymer backbones [7,8]. This system is formed from an arrangement of alternating single and double bonds, so that  $\pi$  electrons are delocalized along the polymer chain rather than localized in a single bond. This delocalization creates energy bands that resemble those of semiconductor materials. The more regular the  $\pi$  conjugation, the easier it is for electrons to move, thus increasing the conductivity. The valence orbitals of a material interact with each other to produce a series of molecular orbitals that form bands extending throughout the substance. Similar to the valence electrons of individual atoms, the band of the highest occupied molecular orbitals (HUMO) of a material is called the valence band (VB) (Fig. 1). The band of the lowest unoccupied molecular orbitals (LUMO) is known as the conduction band (CB), because the current in this material can only flow when electrons are stimulated to this band.



**Figure 1:** Energy diagram of conjugated polymers [7]

In their pure (undoped) state, most conductive polymers are semiconductors with low conductivity.

To improve the electrical conductivity, a doping process is performed, either by oxidation (p-type doping) or reduction (n-type doping). In p-type doping, electrons are removed from the backbone, creating positively charged cavities (holes), whereas n-type doping adds electrons to the  $\pi$  system. This process not only increases the number of charge carriers, but also produces quasi-particle species such as polarons (a single charge accompanied by local distortion in the chain) and bipolarons (two charges on one segment). Polarons and bipolarons form new energy levels within the band gap, facilitating charge transfer along the polymer chain [9,10].

The microscopic structure influences the conduction pathway, and the degree of crystallinity, chain orientation, and interchain interactions play crucial roles in determining the charge transport efficiency. In physiological environments, the presence of water and ions can alter doping conditions, destabilize conjugation, or disrupt charge mobility. Therefore, chemical modification, more stable doping, and incorporation with nanomaterials or hydrogels are often employed to maintain optimal conductivity for such applications.

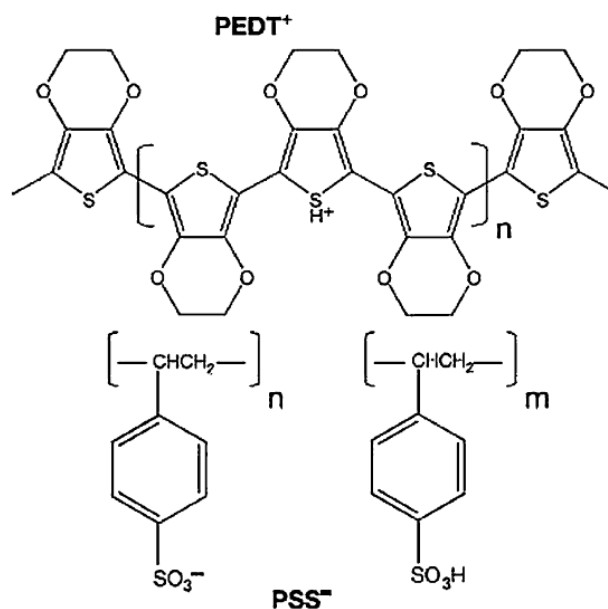
### III. CONDUCTIVE POLYMERS RELEVANT IN BIOMEDICINE

Conductive polymers have become key materials in the development of biomedical devices owing to their electrical properties, flexibility, and chemical modifiability. Certain types of conductive polymers are distinguished by their stability in physiological environments, ability to integrate with biological tissues, and consistent electrical performance.

#### A. Poly(3,4-ethylenedioxythiophene): Polystyrene Sulfonate (PEDOT:PSS)

PEDOT:PSS (Fig. 2) is the most widely used conductive polymer in medical applications because of its high conductivity stability, resistance to degradation, and good biocompatibility. PEDOT:PSS can maintain its performance in aqueous

environments; therefore, it is often used as a flexible electrode material in neural implants, electrophysiological sensors, and tissue stimulation devices. The dopant structure of PSS helps improve its processability in solution form so that it can be printed or coated on various substrates, including hydrogels.[11,12,13].

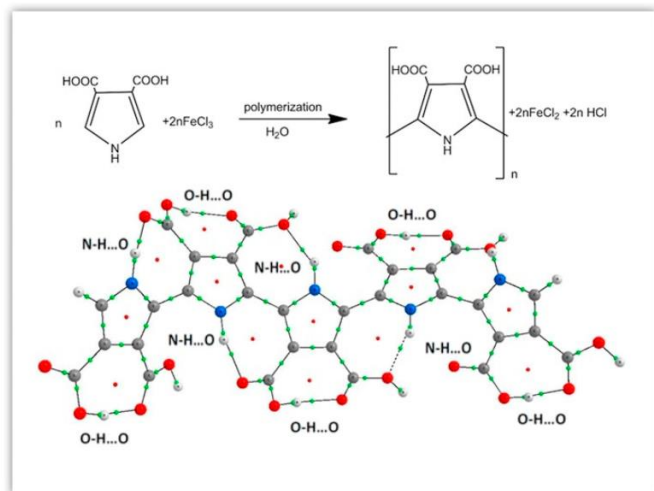


**Figure 2:** PEDOT:PSS complex Conductive Polymer [12]

#### B. Polypyrrole (PPy)

Polypyrrole is a conductive polymer with a crosslinked heterocyclic monomer structure. Its molecular structure consists of five-membered pyrrole rings linked at positions 2 and 5 [14]. Polypyrrole (PPy) has attracted widespread attention owing to its excellent environmental stability, high conductivity, simple synthesis, good biocompatibility, and reversible redox properties. This material can be synthesized through electropolymerization on electrode surfaces, allowing the formation of thin films with precise thickness control. Figure 3 shows the synthesis of polypyrrole 3,4-dicarboxylic acid [15], which was In biomedicine, PPy is widely used as implantable electrodes, electroactive scaffolds for neural and muscle tissue engineering, and electrically controlled drug delivery systems. However, its

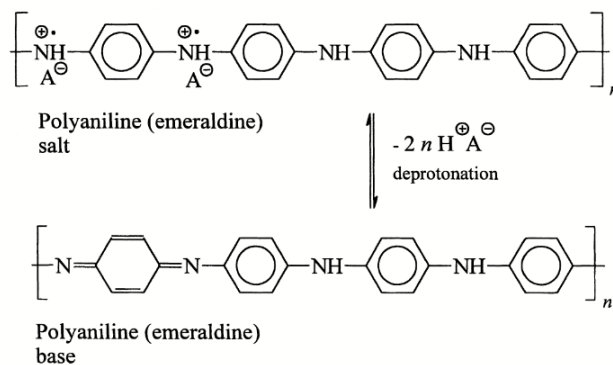
relatively stiff mechanical properties are a drawback; therefore, modification with hydrogels or elastomers is often performed to increase flexibility. [16]



**Figure 3:** Polymerization of polypyrrole 3,4-dicarboxylic acid [15]

### C. Polyaniline (PANI)

PANI has a stable electronic structure and a wide variety of structures that can undergo color changes and conductivity depending on the level of oxidation and pH conditions [18]. Figure 4 shows the deprotonation of the polyaniline polymerization. PANI has high stability in the environment, is easy to synthesize, and undergoes reversible electrical and optical changes through redox reactions and doping/protonation/deprotonation. Therefore, it has great potential for use in various applications. These characteristics make PANI suitable for biomedical applications. In addition, PANI can be easily modified using organic or inorganic dopants to improve its biocompatibility. However, its stability in physiological environments requires improvement. [19,20]



**Figure 4:** Polyaniline (emeraldine) salt is deprotonated in the alkaline medium to polyaniline (emeraldine) base.[18]

### D. Conductive Polymers in Composite Form

Conductive polymers can be combined with biocompatible polymers and conductive fillers, such as graphene, carbon nanotubes, and metal nanoparticles, to improve their mechanical properties and processability [21]. Conductive polymer-based composites enable the development of a wide range of materials for biomedical applications that can be tailored to enhance the material properties that are critical for the long-term performance of implantable devices. Conductive polymers have also been used to successfully impart conductivity to hydrogels and elastomeric polymers [22].

Overall, these various types of conductive polymers offer unique advantages that enable broad applications in modern medical systems, such as implantable devices, biosensors, tissue engineering, electrical stimulation therapy, and smart drug delivery systems. Advances in formulation and chemical modification are enabling conductive polymers to become future materials for biomedical technology.

## IV. CHARACTERISTICS REQUIRED FOR BIOMEDICAL APPLICATIONS

To function optimally in biomedical systems, conductive polymers must meet a number of stringent material characteristic requirements. These characteristics ensure the polymer can interact well

with biological systems and effectively perform its intended function. This is especially important because the devices interact directly with complex, sensitive, and dynamic living tissues.

**A. Poly(3,4-ethylenedioxythiophene): Polystyrene Sulfonate (PEDOT: PSS)**

Conductive polymers must exhibit high electrical conductivity to facilitate signal transfer and improve cell communication, similar to semiconductors [23]. Electrical conductivity indicates the material's capacity to conduct electric current, expressed in units of S/cm. Materials can be considered as insulators (conductivity < 10<sup>-8</sup> S/cm), semiconductors (10<sup>-8</sup> < conductivity < 10<sup>-3</sup> S/cm), and conductors (conductivity > 10<sup>-3</sup> S/cm) [21]. To obtain the desired conductivity characteristics in the range of 10<sup>-12</sup> to 10<sup>-7</sup> S, conductive polymers need to be further modified. The relationship between conductivity ( $\sigma$ ) and resistivity ( $\rho$ ) is given by

$$\sigma = \frac{1}{\rho} \tag{1}$$

The value of  $\rho$  is determined using resistance (R), which is usually measured using the 4-point probe method. In this technique, a constant electric current (I) flows through two electrodes placed on the surface of the material, while the voltage (V) generated through the other pair of electrodes is measured [24]. The relationship between R and  $\rho$  can be seen in the following equation,

$$\rho = R \frac{A}{l} \tag{2}$$

where A and L represent the cross-sectional area (m<sup>2</sup>) and length of the material (m). From this equation, electrical conductivity can also be expressed as:

$$\sigma = \frac{l}{R A} \tag{3}$$

The electrical conductivity of conductive polymer materials can be enhanced by the addition of other conductive materials. The conduction mechanism depends on the distribution of the added particles, either separated or in contact to form a conductive network. Conduction can occur through direct contact between particles or through electron tunneling. [22,25]. These conductive characteristics

are crucial for applications such as biosensors, neural prosthetics, and tissue engineering [21,26].

**B. Biocompatibility**

Biocompatibility is crucial to ensure that polymers do not elicit adverse immune responses when interacting with biological tissues. This property is crucial for applications in drug delivery, tissue engineering, and biomedical implants [27]. Conductive polymers must be able to interact with tissues without triggering excessive immune responses, chronic inflammation, or cytotoxicity. The material must also support cell adhesion, proliferation, and viability, especially when used in long-term implants or tissue engineering. Biocompatibility can be enhanced through surface modification, the use of safe dopants [28], or integration with biopolymers [29].

**C. Mechanical Properties and Flexibility**

The performance of conductive polymers is strongly influenced by mechanical properties. High molecular weight increases modulus and ductility (preventing brittleness), while doping or modification can change strength, stiffness, and toughness, although at the expense of conductivity. Tensile Strength is the maximum stress a material can withstand before breaking or total failure, while Young's Modulus is a measure of the material's stiffness, indicating how much the material stretches (strains) under a given stress within the elastic limit (stress/strain ratio)[30]. Tensile testing of Polymer Poly(3,4-Ethylenedioxythiophene) Poly(Styrenesulfonate) (PEDOT/PSS) shows values ranging from 1 GPa to 2.7 GPa, tensile strength ranging from 25 MPa to approximately 55 MPa, and total strain at break ranging from 3% to 5%, all of which depend on relative humidity[31]. However, exposure to environmental conditions can degrade these properties, as seen with PEDOT/PSS, where tensile strength drops significantly at certain humidity levels. The mechanical properties of conductive polymers can be significantly improved by optimizing their molecular weight. For example, high-molecular-weight polymers exhibit superior flexibility and

mechanical strength, with substantial increases in strain at fracture and toughness. This is important for flexible and elastic electronics applications. Too high stiffness can induce mechanical strain between the material and the tissue, reducing comfort and long-term stability. Therefore, conductive polymers are often combined with hydrogels or elastomers to match their elastic modulus to that of biological tissues. [32]

#### **D. Processability and Material Integration**

Conducting polymers are easily processed into various shapes and structures. Techniques such as electrospinning, electrochemical polymerization, and templating are commonly used for fabricating conductive polymers. Their versatile processability allows for the creation of complex structures required for specific biomedical applications [33].

Materials must be easily fabricated in the form of thin films, fibers, scaffolds [3], or microelectrodes. The ability to be processed using modern techniques such as printing [22], electropolymerization, or solution-based fabrication is essential for their application in wearable devices, implants, or flexible sensors. In addition, compatibility with nanomaterials or biomolecules allows for more sophisticated multifunctional devices [28].

#### **E. Chemical Stability and Controlled Degradation**

For temporary implants and drug delivery systems, biodegradability is a desirable property. Biodegradable conductive polymers can degrade in the body without causing damage, making them suitable for short-term applications. Conductive polymers must maintain their properties under physiological conditions. Chemical stability ensures that the material remains functional for the required duration of application [27]. In long-term applications, polymers must be resistant to oxidation, enzymatic degradation, and structural changes. For certain applications, such as tissue engineering, controlled biodegradation is also required so that the material can degrade without producing toxic products. Chemical stability is also

directly related to the durability of conductivity in the body.

#### **F. Surface Functionalization**

To be used as a bioelectric interface, polymers need to have surfaces that are easily chemically modified. Functionalization allows the binding of biomolecules such as adhesion proteins, bioactive peptides, or growth factors that can enhance biological responses. This is important in the fabrication of electroactive scaffolds [3] or more “cell-friendly” neural electrodes [34]. The surface properties of conductive polymers can be fine-tuned to improve their interaction with biological tissues. This is important for applications such as biosensors and tissue engineering scaffolds.

### **V. APPLICATIONS OF CONDUCTIVE POLYMERS IN BIOMEDICAL SYSTEMS**

#### **A. Biosensor**

Biosensors are devices that detect biological molecules such as glucose, neurotransmitters, enzymes, DNA, or disease biomarkers. Conductive polymers serve as active layers that enhance sensitivity, stability, and detection accuracy through several mechanisms. [5, 35]

##### **1. Signal Transduction Interfaces**

Conductive polymers such as PEDOT: PSS, PPy, and PANI [36] provide platforms that can capture biological changes and transmit them as electrical signals. When biomolecules react on the sensor surface, changes in impedance, current, or potential occur that can be detected in real time.

##### **2. Biomolecule Immobilization**

Immobilization of biomolecules (such as enzymes, DNA) onto conductive polymers (such as polypyrrole, PEDOT) involves techniques such as physical adsorption, covalent bonding, entrapment, or cross-linking, creating functional platforms for biosensors by leveraging the polymer's conductivity for rapid electron transfer, signal enhancement, and improved stability for applications in healthcare, food, and the environment. Methods vary in efficiency, from simple adsorption to strong covalent binding, with strategies

such as electropolymerization directly integrating biomolecules or nanoparticles for enhanced performance [37,38,39].

### 3. Flexibility for Wearable Biosensors

Flexibility is a key factor for wearable biosensors using conductive polymers, contributing to device comfort, performance, and durability. The flexibility provided by conductive polymers is crucial, enabling the creation of wearable biosensors that function effectively and comfortably. Conductive polymers can be processed as thin films, fibers, or patches, making them suitable for flexible biosensors such as dry patches for ECG/EEG, dry biosensors for sweat, and skin sensors for physiological monitoring.[40,41]

### B. Neural Interfaces and Neural Implants

Conductive polymers play a central role in the development of modern neural interfaces and neural implants due to their ability to provide stable, flexible, and biocompatible electrical–biological interfaces. Unlike traditional metals (Pt, Au, Ir), conductive polymers can lower electrode impedance, improve the quality of neural signal recording, and reduce long-term inflammatory responses [6].

A neural interface is a device that connects the nervous system with electronic devices to read, modulate, or stimulate neuronal activity. Conductive polymers act as electrode layers that are in direct contact with neural tissue. The role of the neural interface is to improve signal recording quality, increase nerve stimulation efficiency, and provide mechanical flexibility to reduce trauma. Polymers such as PEDOT:PSS, PPy, and PEDOT-derivatives have much lower impedance than conventional metals of the same size. PEDOT:PSS can reduce electrode impedance by 10–100 times. [42]

Stimulation efficiency is increased because conductive polymers have a high charge capacity, a more homogeneous charge distribution, and stable ion–electron interactions. Implants can provide safer electrical stimulation, with a lower risk of tissue damage. Nervous tissue, especially the brain and

peripheral nerves, is very soft and elastic. Conductive polymers can be made into thin films, elastomers, or electroactive hydrogels so that their elastic modulus approaches that of nerve tissue. This can reduce mechanical friction, micro-inflammation, and glial scarring, which typically occur with hard metal implants. [43]

In neural networks, electrical signals are transmitted through ions (Na<sup>+</sup>, K<sup>+</sup>, Cl<sup>-</sup>). Polymers such as PEDOT:PSS are mixed ionic–electronic conductors, thus being able to efficiently convert ionic signals into electronic signals [42]. This allows for high-sensitivity recording of neuronal activity and electrical stimulation with low energy requirements. In this condition, the surface of conductive polymers can be modified with cell adhesion peptides (RGD), proteins (laminin, gelatin), and neuronal cell growth polypeptides. These modifications improve axon growth, tissue stability at the electrode, and long-term interfacing. Due to their more tissue-compatible mechanical properties, conductive polymers result in lower inflammation, minimal glial response, and long-term signal stability, which is very important for chronic implants [44].

### C. Conductive Polymer-Based Controlled Drug Delivery System

Conductive polymers have become strategic materials in the development of drug delivery systems (DDS) capable of precisely controlling drug release through electrical stimuli. Unlike conventional drug delivery systems that rely on passive diffusion or material degradation, conductive polymers enable on-demand, targeted, and adjustable drug release [45]. This is crucial for therapies requiring precise dosing, such as those for neurodegenerative diseases, cancer, chronic wounds, and neurological disorders.

Conductive polymers such as PPy and PEDOT can undergo changes in charge when given an electrical stimulus. This change triggers the expansion/contraction of the polymer structure or the release of the dopant stored within it. If the dopant is

replaced by a drug molecule, the drug will be released when the polymer is oxidized (losing electrons), releasing drug anions, or reduced (accepting electrons), releasing drug cations. This mechanism is very efficient for charged drugs.[11,12]

In conductive polymers, drugs can function as dopants, which are ions that balance the charge of the polymer backbone. When the doping state changes due to electrical stimulation, the drug will be pushed out. Drugs can be stored by doping-based mechanisms. Anti-inflammatory drugs (e.g., DEX) are stored as anions in PPy and released when the polymer is oxidized. In addition, drug mechanisms can also use mechanisms based on structural changes. Electrical stimulation can change the porosity, volume, conformation of the polymer chain, and physical attachment of the drug. These changes trigger controlled drug release. The next mechanism is the Ionic–Electron Conductivity mechanism. PEDOT:PSS, which is a mixed ion–electron conductor, is able to attract or release ions due to an electric current. This allows for a smoother release of ionic-based drugs, including neutral drugs after modification.[45]

Drug Delivery Systems can be Conductive Polymer Based, in the form of Thin Films or Electroactive Layers. PPy or PEDOT films are used on the surface of implants to provide local anti-inflammatory drug release, prevent scarring, or improve cell integration. In addition, the drug delivery system can be in the form of Electroactive Hydrogels [13]. Conductive polymer hydrogels can respond to electrical stimuli with rapid volume changes, triggering drug release. These hydrogels are very suitable for wound healing, growth factor delivery and tissue therapy that requires controlled moisture. Other forms of Drug delivery are Electroactive Microparticles and Nanoparticles. Here, conductive polymers can be made in the form of nanoparticles to deliver drugs to specific targets. These nanoparticles are responsive to electricity, pH, and body ions.

#### **D. Tissue Engineering and Conductive Polymer-Based Conductive Scaffolds**

The use of conductive polymers in tissue engineering has opened up new opportunities for regenerating tissues that require electrical stimulation, such as neural tissue, skeletal muscle, myocardium, and certain bone tissues. Conductive scaffolds not only provide a physical structure for cells to grow in, but also provide electrical signals that mimic the tissue's natural environment (electrical microenvironment)[3], thereby enhancing cell proliferation, differentiation, and function.

Tissue engineering aims to create or repair body tissues using a combination of cells, scaffolds, and biological/physical stimuli. Conductive polymers provide unique capabilities in the form of electrical stimuli that are very important for electroactive tissues. The role of conductive polymers in tissue engineering is to improve intercellular communication through electrical signals, support cell orientation and alignment, facilitate the growth and regeneration of electroactive tissues, and accelerate tissue healing through small current-based stimulation. Commonly used polymers: PEDOT: PSS, PPy, PANI, PEG-PEDOT, biopolymer-based conductive polymers, and conductive nanocomposites.[3,6,44]

In tissue regeneration, scaffolds function as a three-dimensional framework for cell adhesion, cell migration, extracellular matrix (ECM) formation, and new tissue development. Conductive polymers are often combined with hydrogels, collagen, chitosan, or gelatin to improve biocompatibility. Scaffolds also create an electrical environment that resembles native tissue. Tissues such as muscles and nerves have natural bioelectric activity. Conductive scaffolds are able to conduct electrical signals between cells, increase synaptic connectivity, facilitate axon growth, and accelerate neural tissue regeneration [46,47]. By providing a low external current (mA– $\mu$ A), scaffolds can enhance stem cell differentiation into neurons, myoblasts, or cardiomyocytes, the expression of electroactive genes, and the repair of injured tissue.

### E. Wearable and Flexible Bioelectronics Based on Conductive Polymers

Conductive polymers play a crucial role in the development of wearable devices and flexible bioelectronics, two technologies increasingly dominant in real-time health monitoring, digital therapeutics, and human-machine interaction. The advantages of conductive polymers, such as flexibility, stable conductivity, high processability, and biocompatibility, make them ideal materials for creating devices that can adhere to the skin, follow body movements, or even be integrated into textiles.

Modern wearable devices require materials that are flexible and stretchable, conductive, lightweight, biocompatible, stable to sweat, humidity, and body temperature, and can be made in the form of patches, thin films, electrodes, textiles, or sensors that can be attached to the skin.[48] Conductive polymers such as PEDOT: PSS, polypyrrole (PPy), polyaniline (PANI), MXene–PEDOT composites, and conductive elastomers are ideal candidates for this flexible technology.[49] Conductive Polymer-Based Wearable and Bioelectronics include Skin-Mounted Sensors, Smart Textiles, Flexible Strain and Pressure Sensors, Wearables for Bioelectric Therapy, Wearable Devices for Chemical Detection, and Micro-Implantable Flexible Bioelectronics.

The advantages of Conductive Polymers in Wearables include high flexibility and elasticity so they are not easily cracked when stretched, light and thin so they are suitable for being attached to the skin and biocompatible so they are safe for long-term use. Conductive Polymers in Wearables also have low impedance so that bioelectric signals are clearer, can be processed in various forms such as films, fibers, conductive inks, are easily integrated with microelectronics and have stable conductivity even when exposed to sweat or water vapor.[48,49,50]

Challenges that are still faced in the application of wearable conductive polymers include long-term resistance to sweat (dopant corrosion), decreased conductivity when stretched to the extreme,

delamination from the skin after prolonged use, the need for low-power and durable devices, and the chemical stability of polymers in open environmental conditions. Seeing these challenges, future research solutions are needed in the form of new generation elastomeric conductive polymers, self-healing materials for repairing cracks, ultra-thin flexible ionic conductors, and bioelectronic-AI integration for health analytics. Wearables and flexible bioelectronic devices based on conductive polymers are creating a new era of comfortable, integrated, and high-precision health monitoring. These materials enable devices that follow body movements, provide real-time data, and have the potential to combine diagnostic and therapeutic functions in one lightweight and flexible platform.

## VI. CONCLUSION

Conductive polymers are modern functional materials with significant potential in the biomedical field due to their ability to combine electrical conductivity, flexibility, biocompatibility, and ease of chemical modification. Materials such as PEDOT: PSS, polypyrrole (PPy), and polyaniline (PANI) have demonstrated superior performance as flexible electrodes, biosensor components, neural implant materials, and even as active elements in therapeutic devices and drug delivery systems.

Their  $\pi$ -conjugated electronic structure allows these polymers to conduct electricity stably, while doping and composite modification processes can enhance their performance according to application needs. For use in biological environments, conductive polymers must meet critical requirements such as high conductivity, biocompatibility, mechanical flexibility, chemical stability, and surface functionalization.

Their use has expanded to include biosensors, neural interfaces, electrical stimulus-based drug delivery, conductive scaffolds for tissue engineering, and flexible wearable and bioelectronic devices. Conductive polymers can create more compatible

electronic-biological interfaces than conventional metallic materials, resulting in improved signal performance and reduced tissue response.

However, challenges remain, such as long-term stability in physiological environments, decreased conductivity upon stretching, brittle mechanical properties, and dopant degradation. Future research should focus on the development of elastomeric conductive polymers, self-healing materials, highly conductive yet flexible composites, and integration with artificial intelligence technologies for smarter and more precise medical applications.

Overall, conductive polymers have the potential to become key materials in the innovation of next-generation biomedical devices—from diagnostic systems and therapeutic devices to safer, more flexible, and more functional implantable and wearable technologies.

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