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REVIEW

Advances in Electroconductive Polymers for Biomedical Sector: Structure and Properties

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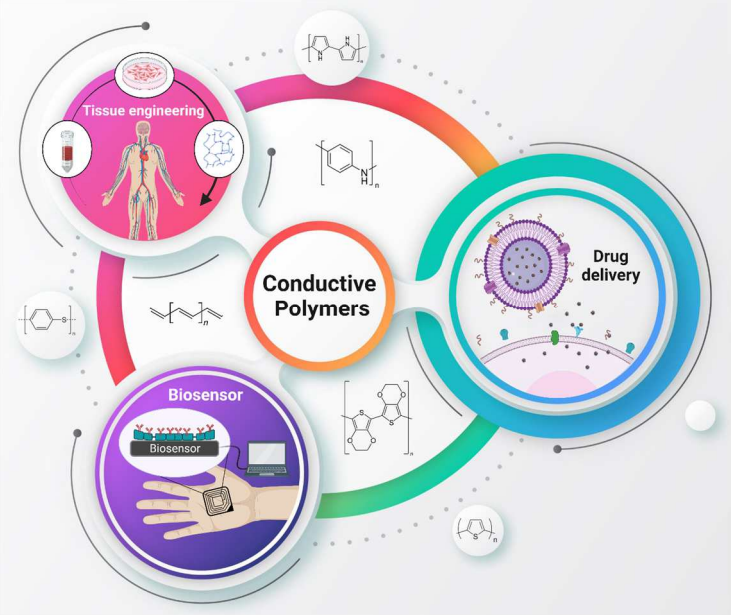
ABSTRACT

This review examines the synthesis, properties, and broad-spectrum applications of electroconductive polymers (ECPs), including polyaniline, polypyrrole, polythiophene, polyphenylene, and polyacetylene. These polymers exhibit high electrical conductivity, versatility in fabrication, and compatibility with various functionalization techniques, making them particularly attractive for diverse applications. While ECPs have traditionally been used in sensors, actuators, and energy storage systems, their utility extends much further, most notably to the realm of biomedical applications. The review meticulously explores the synthesis techniques of ECPs, shedding light on both chemical and electrochemical methods, and the pivotal role that dopants and polymerization techniques play in shaping the properties of the resultant polymers. Apart from discussing the conventional applications of ECPs, the review devotes substantial attention to their groundbreaking biomedical applications, like tissue engineering, medical implants, and the creation of interfaces with biological tissues. It also underscores the future trajectory of ECP research, emphasizing the development of innovative materials and fabrication methodologies for more advanced applications. With this holistic analysis of the field, the review seeks to enhance readers' understanding of the intrinsic properties, structural complexities, and fabrication nuances of ECPs, and inspire continued research and development in this fascinating and consequential domain of materials science.



Keywords: Electroconductive polymers, polyaniline, polypyrrole, polythiophene, polyphenylene, polyacetylene

1. Introduction

The majority of polymers are insulators due to the strong covalent bonding between atoms in their chains, which results in the absence of free-moving electrons or ions [1, 2]. However, for medical implants in cardiac, nerve, and skeletal muscle tissues, this lack of electrical conductivity presents a significant drawback [3]. To achieve a fully functional restoration, medical implants in these tissues need to exhibit a certain level of electrical conductivity. Electroconductive polymers (ECPs) are organic materials that possess unique electrical and optical properties, similar to those of inorganic semiconductors and metals [3, 4]. They can be synthesized using cost-effective approaches and

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can be assembled into supramolecular structures with multifunctional capabilities. ECPs have demonstrated promising capabilities to induce various cellular mechanisms, which broadens their unique applications in the biomedical field [4]. They are attractive for various biomedical applications due to their intelligent response to electrical fields from different types of tissues. ECPs have been used to enhance the electrical sensitivity, speed, and stability of various biomedical devices and their interfaces with biological tissues.

There are five common types of ECPs: polyaniline, polypyrrole, polythiophene, polyphenylene, and polyacetylene. The electrical conductivity (S/cm) of these ECPs and their abbreviations are shown in **Table 1**. In addition to these polymers, conductive composite polymers, such as π-conjugated ECPs, conductive nanoparticles, carbon-based nanoparticles, and alloys, have also been extensively studied [5].

ECPs have several potential applications, including electrically induced targeted drug release systems, biosensors, and metabolic markers of stress [6]. Moreover, the clinical applications of ECPs are vast, including the development of nerve conduits, synthetic scaffolds that support the successful regeneration of myocardial tissue, and deep brain stimulation for the treatment of neurological disorders such as Parkinson's disease. There are still many potential uses of ECPs, from biosensors and bioactuators to drug delivery systems and neural prosthetics [7-9].

This manuscript presents an in-depth study of the structure and properties of ECPs, including their electrical and optical properties, which directly influence their performance in biomedical applications. The manuscript not only discusses the potential applications of ECPs, such as in tissue engineering, regenerative medicine, biosensors, and neural prosthetics, but also the challenges in their development, including the need for biocompatibility, stability, and enhanced mechanical properties. Furthermore, the review provides novel insights into the methods for modifying ECPs to enhance their biocompatibility and reduce toxicity. It discusses innovative approaches such as surface modification, polymer blending, and preconditioning techniques. The manuscript also brings to light the key advantages of ECPs in the biomedical field, such as cost-effectiveness, low detection limit for biosensors, chemical stability, good processability, tunable electrical properties, and stimuli responsiveness. In essence, this manuscript presents a novel, well-rounded perspective on the use and potential of ECPs in the biomedical field, making it a valuable resource for researchers and industry professionals alike.

Table 1. Conductivities of common types of electroconductive polymers [3]

Electroconductive polymers	Abbreviation	Formula	Conductivity (S/cm)
Polyaniline	PANI	$[C_6H_4NH]_n$	10^{-2}-10^{0}
Polypyrrole	PPy	$[C_4H_2NH]_n$	2-100
Polythiophene	PT	$[C_4H_4S]_n$	10^{0}-10^{3}
Poly(p-phenylene)	PPP	$[C_6H_4]_n$	10^{-3} –10^{2}
Polyacetylene	PA	$[C_2H_2]_n$	10^{5}

2. Common types of ECPs

2.1. Polyaniline (PANI)

Polyaniline (PANI) is a highly regarded ECP due to its easy preparation, cost-effectiveness, high electrical conductivity, biocompatibility, low toxicity, and environmental stability [10]. However, it has certain drawbacks, such as low solubility, insolubility in common solvents, infusibility, weak processability, and decreasing electrical conductivity over time [11]. To address these limitations, various techniques have been developed, including re-doping with functionalized organic acids, copolymerization with PANI derivatives or other polymers, and preparing blends and nanocomposites with various materials [12].

PANI nanocomposites are highly promising ECP nanocomposites as they combine the PANI matrix with conducting or insulating nanofillers to enhance their properties. These nanocomposites have improved properties, making them valuable in various fields such as electronics, water purification, tissue regeneration, and antimicrobial therapy.

PANI or "aniline black" is one of the oldest ECPs, discovered in the mid-19th century. PANI molecular structure may possess benzenoid, quinonoid units, or both types in different proportions [13]. Chemical and electrochemical oxidative polymerization are the most common methods for synthesizing PANIs in an acidic medium. Ammonium

persulfate and potassium persulfate are the most widely used initiators for chemical polymerization. The electrochemical method is preferred for small-scale synthesis, while the chemical method allows large-scale polymer and nanocomposite preparation [14]. The electrode coating and co-deposition approaches are two electrochemical methods used for PANI synthesis. PANIs of various nanostructures with different properties have been synthesized using several techniques, such as solution, self-assembling, heterophase interfacial, and electrochemical polymerizations. PANI nanostructures, such as nanospheres, nanogranules, nanorods, nanoflowers, nanofibers, and nanotubes, have been synthesized using different procedures and parameters, including the initiator or oxidant, pH, temperature, solvent, chemical additives, chemical oxidation process, template, electrochemistry, radiochemistry, and sonochemistry. The electrical properties of PANI-based polymers depend on their microscopic and macroscopic properties.

PANI is chemically stable and structurally resistant in acidic and alkaline solutions, without any degradation or chemical reaction. Depending on the redox states, PANI has different solubility in common organic solvents. PANI pellets demonstrate superior mechanical strength due to the good compactness of the PANI powders. The physical and mechanical properties of PANI nanocomposites, such as Young's modulus and heat resistance, are significantly improved. **Figure 1** displays the various oxidation forms of PANI. PANI has shown promise in the field of biomedicine. It possesses biocompatibility and can interact with biological systems, making it suitable for applications such as drug delivery, tissue engineering scaffolds, and biosensors. Polyaniline-based materials have been explored for their potential in controlled drug release, cell culture substrates, and bioelectrodes, among others [4].

However, challenges remain in optimizing and expanding the applications of PANI. These include improving its stability under prolonged exposure to environmental factors, enhancing its processability for large-scale production, and addressing potential issues related to its long-term performance and compatibility in specific applications.

In summary, PANI is a versatile conducting polymer with excellent electrical conductivity, environmental stability, and tunable properties. Its broad range of applications spans from electronics and energy storage to corrosion protection, biomedical devices, and beyond. Ongoing research and development efforts continue to explore and unlock the full potential of polyaniline in various fields, driving advancements in materials science and technology.

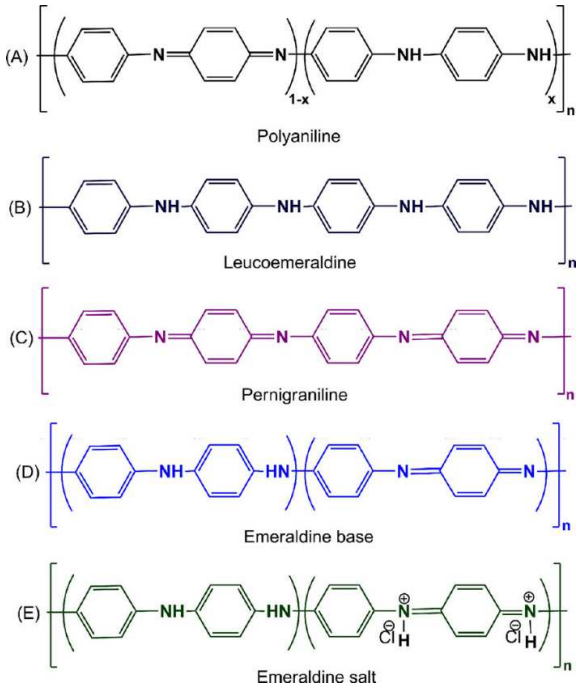

Figure 1. Different oxidation forms of polyaniline. Reprinted with permission from [4]

2.2. Polypyrrole (PPy)

Polypyrrole (PPy) is a type of polymer that has gained attention for its excellent electrical conductivity, which makes it a promising candidate for electronic applications. The polymer's high conductivity is primarily attributed to the polymer backbones that facilitate the easy movement of electrons within and between them [15]. PPy has a conjugated backbone with alternating single and double bonds with sp^2-hybridized carbon atoms. The electrical conductivity of PPy changes from an insulator to a semiconductor, with a band gap < 2.5 eV, once it is doped [16].

The doping process creates polarons and bipolaron species that enhance the electrical conductivity of PPy. The exact mechanism of charge transfer in a PPy chain has not been fully elucidated, but it is believed that polarons and bipolarons are created during the doping process [17].

Polarons are π-conjugated structures based on aromatic rings that are formed from the elimination of an electron from the p system of PPy, generating a free radical and a cation [18]. The radical cation then undergoes a bond rearrangement to form a quinonoid system. In general, species with two charges in the same unit cell are termed a bipolaron, regardless of whether the species are stable or not. Doping may be performed chemically, electrochemically, or by using photo-doping, and organic and inorganic dopants have been used for doping PPy [19]. Small and large molecule dopants modulate the electrical conductivity and the surface structural properties of PPy in different fashions, with larger dopants enhancing the electrochemical stability of the synthesized PPy.

Apart from doping, the electrical conductivity of PPy is affected by the type of oxidant, the initial oxidant/pyrrole molar ratio, synthesis procedure, reaction duration, and temperature. The surfactant concentration also plays a significant role in the formation of PPy structures with different morphologies. The electrical conductivity of PPy synthesized using oxidants such as $FeCl_3$ or ammonium persulfate increases with the temperature of the reaction.[20] The electrical conductivity of PPy synthesized using FeCl3 as an oxidant was higher than when synthesized with ammonium persulfate as an oxidant, both in the presence of an anionic surfactant such as sodium dodecyl sulfate. This may be due to the difference in chemical structure between the two oxidants, and the interaction of pyrrole with sodium dodecyl sulfate during the synthesis [21, 22]. **Figure 2** shows the electrochemical and chemical synthesis methods of PPy.

PPy exhibits good biocompatibility, which makes it suitable for biomedical applications. It can be utilized in drug delivery systems, tissue engineering scaffolds, and bioelectrodes due to its ability to interface with biological systems. The biocompatible nature of PPy, combined with its electrical conductivity, provides opportunities for bioelectronic devices and neural interfaces [23].

As with any material, there are ongoing research efforts to optimize and improve the performance of PPy. Scientists are exploring various strategies to enhance its conductivity, tailor its properties, and expand its functionality. This includes incorporating different dopants, composites, and nanostructures into the PPy matrix to achieve specific characteristics and performance enhancements.

In conclusion, PPy stands as a highly versatile and intriguing conducting polymer, renowned for its exceptional electrical conductivity, redox properties, processability, and optical characteristics. Its broad range of applications spans from electronics and optoelectronics to biomedicine, offering promising avenues for technological advancements and innovations.

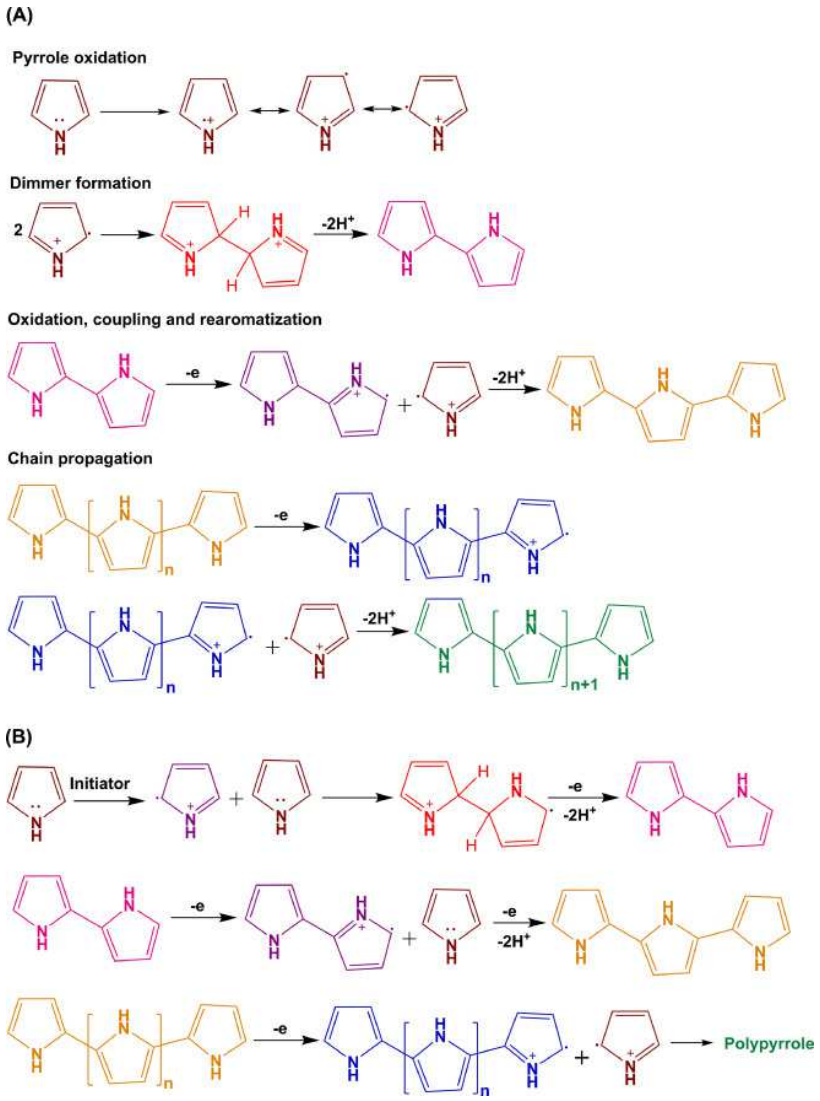

Figure 2. Electrochemical **(A)**, and chemical **(B)** synthesis methods of polypyrrole. Reprinted with permission from [24]

2.3 Polythiophene (PT)

Polythiophene (PT) is a type of conjugated polymer that exhibits stable conductivity and high electrical conductivity [5]. PT is nontransparent and refractory, but its transparency can be increased by dilution through various methods such as block copolymerization, alkyl side chain grafting, blending with a transparent polymer, producing composites, plasma polymerization, electrochemical procedures, and thin layer PT deposition [25].

PT has garnered considerable interest in both research and industrial sectors due to its exceptional environmental stability, improved thermal stability, and reduced band gap energy. These desirable properties, coupled with their semiconducting, electronic, and optical activities, as well as their superior mechanical characteristics and ease of processing, have generated significant attention towards PT composites. PT has found extensive application in solar cells due to its ability to establish improved contact with metal electrodes and its stability under ambient conditions. The PT matrix serves as an efficient polymer for transporting holes, making it highly compatible with semiconducting particles. This combination creates a new hybrid variety with exceptional electrical properties. Furthermore, PT stands out as an excellent ECPs, due to the conjugated double bonds in the polymer backbone. Similar to other conducting polymers, the conductivity of the PT matrix can be enhanced by inducing polarons and bipolarons through oxidation or reduction processes. This flexibility allows for the utilization of PT in various applications such as polymer

batteries, electrochromic devices, and solar cells. In summary, the unique properties of PT, including its compatibility with metal electrodes, stability, hole transport capability, optical transparency, and intrinsic conductivity, have made it highly sought-after for use in solar cells, electrochromic devices, and polymer batteries. By leveraging these distinctive characteristics, PT has demonstrated its potential for enhancing electrical and optical performances in these technologies. Furthermore, the simplicity of polymerization and the air stability of PT makes it even more significant compared to other conducting polymers [26, 27].

2.4 Poly(p-phenylene) (PPP)

Poly(p-phenylene) (PPP) is a conducting polymer that has attracted considerable attention due to its excellent electrical conductivity. PPP is composed of repeating units of p-phenylene, which consists of benzene rings connected by carbon-carbon single bonds. PPP exhibits high conductivity primarily due to its extended conjugated structure. The delocalized π-electron system along the polymer chain allows for the efficient movement of electrons, facilitating electrical conductivity. The alternating single and double bonds in the p-phenylene units create a favorable pathway for electron delocalization and transport [28].

To enhance the conductivity of PPP, various materials have been hybridized with it, including zinc oxide nanoparticles, silicate platelets, polystyrene mixtures, amino or carboxyl groups, poly-L-lysine, and (diphenylamino)-s-triazine. Moreover, the electrical conductivity of PPP can be further enhanced by controlling its oxidation state. By oxidizing the polymer through chemical or electrochemical methods, PPP can undergo doping, resulting in the introduction of charged species into the polymer structure. This process, known as p-doping, increases the number of charge carriers and thus enhances the electrical conductivity of PPP. The conductivity of PPP can also be influenced by the presence of impurities, defects, or dopants in the polymer matrix. The introduction of dopant molecules can lead to the formation of charge transfer complexes, which contribute to enhanced electrical conductivity. Techniques such as fluorination and sulfonation have also been employed [14, 29, 30].

The high conductivity of PPP makes it suitable for various electronic and optoelectronic applications. It can be utilized as a conductive coating or electrode material, as well as in organic electronic devices such as transistors, sensors, and light-emitting diodes (LEDs). PPP's conductivity, combined with its good processability and mechanical properties, makes it a promising candidate for integrating electronic functionalities into flexible and lightweight devices. However, it is worth noting that the electrical conductivity of PPP can be influenced by factors such as molecular weight, crystallinity, processing conditions, and the presence of defects. Researchers are actively exploring different strategies to further improve the electrical conductivity of PPP and optimize its performance in various applications [30-32].

In summary, PPP is a conducting polymer with remarkable electrical conductivity. Its extended conjugated structure and ability to undergo doping enable efficient charge transport. The high conductivity of PPP opens up opportunities for its utilization in electronic and optoelectronic devices, contributing to advancements in the field of organic electronics.

2.5 Polyacetylene (PA)

Polyacetylene (PA) is a macromolecule that has garnered much attention in the scientific community due to its unique and multifaceted properties. It is a conjugated polymer that displays electrical conductivity, photoconductivity, gas permeability, supramolecular assemblies, chiral recognition, helical graphitic nanofiber formation, and liquid crystal behavior. The chemical structure of PA is a linear polyene chain, where the backbone provides a platform for decoration with pendants. The presence of repeated units of two hydrogen atoms in the backbone allows for the substitution of hydrogen with one or two substitutes, resulting in monosubstituted or disubstituted PAs, respectively (**Figure 3**). PA can be synthesized using various methods. One of the methods is Ziegler-Natta catalysis, which involves the use of titanium and aluminum in the presence of gaseous acetylene [33]. By adjusting the temperature and amount of catalyst, PA can be synthesized while monitoring the structure and final polymer products. Alternative methods of polymerization radiations, such as glow discharge, ultraviolet, and Y-radiation, could also be used to synthesize PA, which eliminates the use of catalysts and solvents [34].

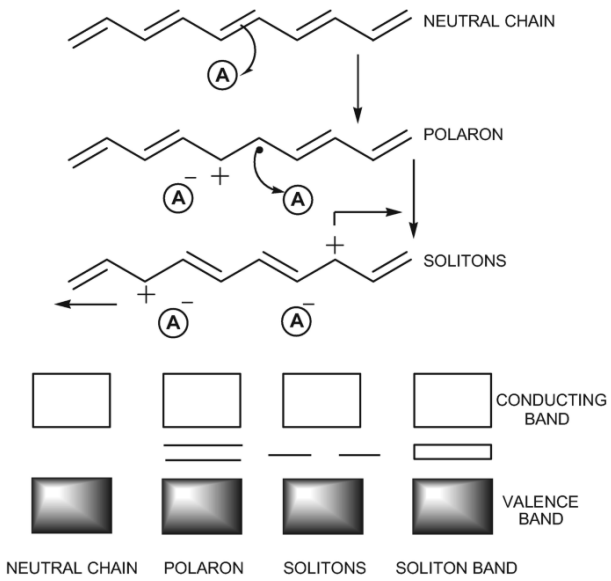

Figure 3. Mechanism of electrical conductivity of polyacetylene. Reprinted with permission from [35]

3. Properties and applications of ECPs

The structure and properties of ECPs play a crucial role in determining their performance in biomedical applications. ECPs typically possess alternating single and double bonds, which form π-conjugated systems that give them unique properties in electrical and electrochemical applications. The presence of π-conjugated systems within the polymer structure allows for the delocalization of electrons, resulting in electrical conductivity. The extent of conjugation and the degree of doping heavily influence the conductivity of the polymer. Higher conductivity is desirable for applications such as electrodes, biosensors, and neural interfaces, where efficient electrical communication is required [30, 36-38].

The most significant factors that influence ECPs are their degree of crystallinity, conjugation length, and interactions within and between chains. These aspects have been identified as having the most significant impact on the properties of ECPs [39]. Moreover, the mechanical properties of ECPs, including flexibility, elasticity, and strength, determine their ability to withstand deformations and mechanical stresses. Flexible and stretchable polymers are desirable for applications in wearable devices, implantable electronics, and tissue engineering scaffolds to ensure compatibility with the surrounding tissues and enhance long-term performance [40, 41].

The electrical conductivity of a substance is determined by its structure, which can be categorized into three types: conductive, semiconductive, and insulating. The energy band theory is useful in classifying materials based on their electrical properties [42]. Conductive materials have an overlapping valence and conduction band, allowing electrons to move freely in the conduction band. In semiconductors, the energy gap between the valence and conduction bands is small, allowing for intrinsic electron transfer with low energy. Insulators have a large energy gap between the two bands, making it difficult for electrons to move through the material. However, these categories do not necessarily apply to ECPs, which require molecular-level studies to determine their conductivity [18, 43]. ECPs achieve electrical conductivity through the sharing or propagation of charges along their backbone, which consists of alternating single and double bonds. This creates an unpaired π electron per carbon atom, and the sp2pz hybrid configuration of carbon atoms allows for delocalized electrons within the polymer chain. This results in charge mobility throughout the polymer structure, enabling features such as electrical conductivity, low energy light transmission, and low ionization potential [44].

The presence of both single and double bonds, including σ and π-bonds, allows for electron flow and electrical conductivity in ECPs [30, 45]. To enhance their electrical conductivity, dopant materials can be introduced to these

polymers. The addition of various chemical species during the polymerization or synthesis process can lead to the formation of nonlinear defects such as solitons, poles, dipoles, and electrical contributions [46, 47]. These dopant materials can be adjusted to control the density and mobility of charge carriers.

The electrical conductivity of polymers is dependent on several factors, including the degree of doping, the arrangement of the polymer chains, the conjugation length of the polymer composition, and the purity of the samples. It should also be noted that the methods used to produce high conductivity in polymers and inorganic semiconductors differ, and thus different conductivities can be achieved depending on the percentage of doping species present in the degraded polymers [47].

To gain a deeper understanding of the electronic structure of ECPs, it is essential to investigate their optical properties. The spectrophotometric spectrum can reveal the color and electron spectrum of polymers, particularly when associated with other compounds such as dopants. The variation of optical spectra during the doping process is crucial as it can provide insights into the nature and mechanism of charged species in the polymer chain [48].

Conjugated polymers have large and rapid nonlinear light response properties that can be fine-tuned through adjustable solution processing. The degree of electron localization (conjugation) and the combination of transition metals with polarizable electrons can increase the hyperpolarizability of materials. The nonlinear optical response of conjugated polymers depends on several factors, including the conjugate length, the orientation of the polymer skeleton, and the relative orientation and structural properties of the chromophore complex and Schiff base metal complexes. The presence of π-bonds in the skeleton of conjugated polymers enables photon-electron interaction and shows an anisotropic electron or quasi-one-dimensional structure [49].

The electronic behavior of organic semiconductors is influenced by the effect of charge stimuli, such as solitons, polarons, or bipolarons in the ground state degeneracy. In conjugated polymeric skeletons, the optical transitions occur due to the release of charge from dopants or from the transfer of oscillator strength from π to π*. Conjugated polymers exhibit behavior similar to semiconductors in their pristine state and behave like metals when doped with dopants (n-type or p-type) [33].

ECPs have gained significant attention in the biomedical sector due to their unique properties and advantages over traditional materials including: (i) Low cost: ECPs can often be synthesized using relatively inexpensive methods and materials, which can lead to cost-effective production compared to traditional materials like metals or inorganic semiconductors. This advantage contributes to the potential for widespread adoption of ECPs in the biomedical sector [50-52]; (ii) Low detection limit: ECPs can be used to prepare biosensors that enable real-time, point-of-care testing. These devices have a low detection limit, which can ultimately result in increased access to treatment [50]; (iii) Chemical stability: Polymeric materials possess chemical stability, which makes them more durable and long-lasting [48]; (iv) Good processability: ECPs can be processed using various techniques, including solution casting, 3D printing, and electrospinning. This processability allows for the fabrication of complex shapes, structures, and patterns, making them suitable for applications that require precise geometries, such as tissue engineering scaffolds or microfluidic devices [48, 53]; (v) Tunable electrical properties: ECPs have tunable electrical properties, which means they can be tailored to meet specific requirements for different biomedical applications. This property allows for the development of electronic components, such as sensors, electrodes, and actuators, which are crucial for many biomedical applications [30]; (vi) Stimuli Responsiveness: Some ECPs exhibit stimuli responsiveness, meaning their electrical or mechanical properties can be altered in response to external stimuli, such as temperature, pH, or light. This property can be harnessed for applications like drug delivery systems, where controlled release of medication can be achieved by applying a specific stimulus [40, 52].

The development of ECPs for biomedical applications is accompanied by several challenges. Ensuring biocompatibility is a significant challenge for ECPs. Some polymers may exhibit inherent cytotoxicity or cause adverse reactions when in contact with living tissues. Modifying ECPs can be done in several ways to enhance their biocompatibility and reduce toxicity: (i) Surface Modification: Modifying the surface of ECPs is a common approach to improving their biocompatibility. This can be achieved by functionalizing the polymer surface with bioactive molecules, such as peptides, proteins, or carbohydrates. These bioactive moieties can promote cell adhesion, prevent protein adsorption, and modulate the immune response, leading to enhanced biocompatibility [40, 41, 54]; (ii) Polymer Blending: Blending ECPs with biocompatible polymers can result in hybrid materials with improved biocompatibility.

By combining the advantageous properties of both polymers, such as electrical conductivity and biocompatibility, the resulting blend can exhibit enhanced performance in biomedical applications. The choice of the biocompatible polymer and the blending ratio should be carefully optimized to achieve the desired properties [54-56]; (iii) Preconditioning and Surface Treatments: Preconditioning techniques such as sterilization, plasma treatment, or UV irradiation can modify the surface properties of ECPs, improving their biocompatibility. These treatments can alter surface chemistry, charge, or roughness, thereby reducing toxicity and promoting favorable cellular responses [57-60].

Moreover, ECPs may be susceptible to degradation, especially under physiological conditions or in the presence of reactive species. This can lead to a loss of electrical conductivity or structural integrity over time. To address this challenge, researchers can explore strategies such as polymer synthesis optimization, crosslinking, encapsulation, or the use of protective coatings to enhance stability and resistance to degradation [40, 41, 54, 59].

While ECPs may possess good electrical conductivity, their mechanical properties, such as strength, flexibility, or stretchability, may need improvement to meet the demands of biomedical applications. Strategies like polymer blending with elastomers or reinforcement with nanofillers can enhance the mechanical properties and tailor them to specific application requirements [40, 41, 51, 55, 61].

The long-term performance and stability of ECPs in the body are also essential for successful biomedical applications. Factors such as biostability, resistance to fatigue, and biodegradation (if desired) need to be carefully considered and addressed during the design phase. Long-term in vivo studies can provide insights into the behavior of ECPs over extended periods and help identify potential challenges and necessary improvements [59, 62, 63].

4. Future perspective of ECPs in the biomedical sector

The future of ECPs in the biomedical sector holds great promise. As research and development efforts continue, we can expect significant advancements and the emergence of new applications. Here are some potential areas where ECPs could have a notable impact in the near future: (i) Implantable Medical Devices: ECPs can revolutionize the field of implantable medical devices, such as neural interfaces, bioelectrodes, and cardiac devices. These polymers can provide enhanced biocompatibility, flexibility, and conductivity, enabling improved long-term performance and biointegration. They can facilitate better communication with the body's tissues and nerves, allowing for more precise control and feedback in therapeutic interventions [64-66]; (ii) Tissue Engineering and Regenerative Medicine: ECPs have the potential to play a critical role in tissue engineering and regenerative medicine. By incorporating electroconductive scaffolds or hydrogels, these polymers can provide electrical cues to guide cell behavior and enhance tissue regeneration. They can aid in the development of functional engineered tissues, such as cardiac patches, neural grafts, or muscle constructs, with the ability to integrate and communicate with the surrounding host tissue [40, 54, 59, 67]; (iii) Wearable and Flexible Electronics: The field of wearable electronics can benefit significantly from the properties of ECPs. These polymers can enable the development of flexible, stretchable, and conformable electronic devices that can be comfortably worn on the body. Applications could include smart textiles, wearable biosensors for health monitoring, electronic skin for prosthetics, and advanced human-machine interfaces [68-71]; (iv) Controlled Drug Delivery Systems: ECPs can be utilized in the development of controlled drug delivery systems. By incorporating drugs or therapeutic agents within the polymer matrix, they can enable controlled and localized release based on external stimuli or specific physiological conditions. These systems can improve the efficacy and safety of drug delivery, particularly in areas such as cancer therapy, chronic pain management, or wound healing [72-75]; (v) Bioelectronics and Bioresponsive Interfaces: ECPs can be employed in the development of bioelectronic interfaces that bridge the gap between biological systems and electronic devices. They can enable direct communication and signal transduction with biological entities, such as neurons or cells, for applications in neuroprosthetics, bioelectronic implants, or brain-computer interfaces. The unique properties of ECPs can facilitate the development of bioresponsive interfaces that can sense and adapt to dynamic physiological conditions [54, 55, 59, 61]; (vi) Biosensors and Diagnostics: ECPs can be utilized in the development of biosensors and diagnostic devices for various healthcare applications. These polymers can serve as transducing elements in sensors, enabling the detection and quantification of biomarkers or analytes. Their electrical conductivity can be modulated by the presence

of specific molecules, facilitating highly sensitive and selective detection, potentially leading to advancements in point-of-care diagnostics and personalized medicine [40, 55, 61, 76].

It is important to note that while these potential applications hold promise, further research, development, and validation are necessary to ensure the efficacy, safety, and reliability of ECPs in real-world biomedical settings. Nonetheless, the unique properties of ECPs make them a highly promising class of materials with the potential to revolutionize various aspects of healthcare and improve patient outcomes.

5. Conclusions

In conclusion, ECPs are emerging as a fascinating class of materials with a unique set of properties, extending their appeal to a broad spectrum of applications. This review serves as a comprehensive resource encompassing the synthesis, characteristics, and implementation of some of the most extensively studied ECPs, namely PANI, PPy, PT, PPP, and PA. The discourse underlines the significance of comprehending the intrinsic link between the structure and properties of ECPs, whilst considering how varying factors such as dopants, polymerization techniques, and processing conditions can alter their attributes. Furthermore, the review furnishes an exhaustive insight into the application of ECPs in diverse biomedical sectors, from biosensors to tissue engineering, highlighting recent strides and existing challenges in these fields. As the realm of ECP research continues to expand, upcoming endeavors should concentrate on devising innovative materials and fabrication methodologies for sophisticated applications. Given their potential to dramatically reshape sectors including electronics, energy, and healthcare, ECPs constitute a compelling and pivotal field within materials science. Anticipation surrounds the future of ECPs, as they are poised to continue drawing considerable interest in the foreseeable future.

Authors' contributions

All authors contributed to drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

Declaration of competing interest

The authors declare no competing interest.

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