ACCSCIENCE PUBLISHING

Explora: Environment and Resource

REVIEW ARTICLE

Environmentally benign conducting polymers: A sustainable approach to biomedical devices

Imene Bekri-Abbes* and **Nour Guetif**

Laboratory of Composite Material and Clay Minerals, National Center of Material Science, Technopole of Borj Cedria, Soliman, Tunisia

Abstract

The rising issue of biomedical discharges underscores the need for sustainable alternatives, leading to emerging applications of biodegradable conducting polymers (CPs). This review aims to emphasize current progress in this research area, focusing on applications for "green" biomedical uses. Novel biomaterials are distinct from others by virtue of their electrical conductivity, while being biocompatible and biodegradable such as conventional biomaterials, making them very suitable for biomedical applications that require safe, controlled degradation within the human body. In addition, the paper draws on current progress in the synthesis of conducting and novel biomaterials, as well as in the processes for controlled degradation, and also addresses their utilization in biomedical applications within biodegradable systems. Essential details on CPs synthesis, with a focus on their emerging applications ranging from temporary biomedical implants to tissue engineering and bioresorbable biosensors, are also discussed. Finally, this review aims to address essential issues and future research for prompt clinical applications and continuous innovations in emerging applications of conducting, biodegradable biomaterials.

Keywords: Medical waste; Biodegradable conducting polymers; Biomedical applications; Sustainable materials

***Corresponding author:**
Imene Bekri-Abbes
(bekrimene@gmail.com)

Citation: Abbes I, Guetif N. Environmentally benign conducting polymers: A sustainable approach to biomedical devices. *Explora Environ Resour.* 2025;2(4):025350063. doi: 10.36922/EER025350063

Received: August 30, 2025

Revised: November 28, 2025

Accepted: December 5, 2025

Published online: December 23, 2025

1. Introduction

Since the groundbreaking discovery of conducting polymers (CPs), this fascinating class of organic materials has received considerable attention because of their unique combination of metallic conductivity and processability comparable to conventional polymers.[1] Their characteristic properties, such as light-weight, flexibility, and adjustability, have already found numerous applications in electronic displays, ranging from sensors and transistors to flexible electronics. The capability to control their properties perfectly while in thin-film format is cementing their position in the emerging biomedical applications domain. Despite this, the lack of biodegradability is still a significant disadvantage in the case of conventional CPs, posing numerous issues in the long run, particularly in the context of biomedical applications.[1] Owing to the increasing demand within the biomedical sector for sustainable alternatives, the emergence of CP materials with biodegradable properties represents one of the most significant requirements within this research field.[2] The presence of biodegradable properties within CP biomaterials not only addresses the issue of biomedical waste but also helps in the development of biomedical devices

with transient properties engineered to degrade within the body.[2] The process of making CP biomaterials begins with the development of composites through the addition of other biomaterials, such as poly (lactic acid) (PLA) and poly(ε-caprolactone) (PCL), or other natural biomaterials.[3] Although this approach significantly enhances the sustainability of CP biomaterials, there is often a decline in electrical properties, mainly owing to issues with electrical interfaces.[3] Recent innovations within this research field have been based on more advanced approaches. These are based on the synthesis of CP biomaterials through modified biomaterials, the addition of degradable links within the polymer, and the development of oligomers based on controlled degradation properties.[3]

This review examines the latest advances in the development of the biodegradable CP for use in biomedical applications, emphasizing the approaches used in designing and making CP. The prospects of this material in shaping the development of sustainable biomedical technology, as well as outlooks and research opportunities in this field, are also discussed.

2. Fundamentals of conducting biodegradable polymer

2.1. Structure and conductivity

The development of CPs emerged in the 1970s with the breakthrough discovery of polyacetylene-enhanced conductivity upon doping. This finding sparked widespread interest, leading to the exploration of diverse polymers such as polypyrrole (PPy), polyaniline (PANi), and poly(3,4-ethylenedioxythiophene) (PEDOT). These materials derive their unique electrical properties from a molecular structure featuring alternating single and double bonds, forming a conjugated system that enables efficient charge mobility through electron delocalization. CPs serve as a vital link between flexible organic materials and highly conductive metals.[4-6] Their molecular architecture, as depicted in Figure 1, includes a range of structures such as polyacetylene derivatives, heterocyclic polymers such as PPy and PEDOT, and aromatic systems like PANi, each tailored for specific electronic applications. The hallmark of CPs is their π-conjugated backbone, where alternating σ- and π-bonds create pathways for electron movement.[7] In their undoped state, these polymers show low conductivity, usually around 10^{-10} S/cm, which makes them insulators. Doping, through either oxidation (p-doping) or reduction (n-doping), introduces charge carriers such as polarons or bipolarons. This boosts conductivity to levels similar to that of metals, within the range between 10^2 and 10^3 S/cm. Doping is a crucial process that turns CPs into highly conductive materials. For instance, p-doping involves removing electrons from the polymer chain, creating mobile positive charge carriers that help with electrical conduction.[8] This ability to adjust, along with the natural flexibility and processability of CPs, makes them great for uses in flexible electronics, sensors, and biomedical devices. However, the strong conjugated systems that give them conductivity also make traditional CPs resistant to natural breakdown. This creates environmental issues, especially for short-term applications such as biodegradable implants or disposable sensors. The long lifespan of conventional

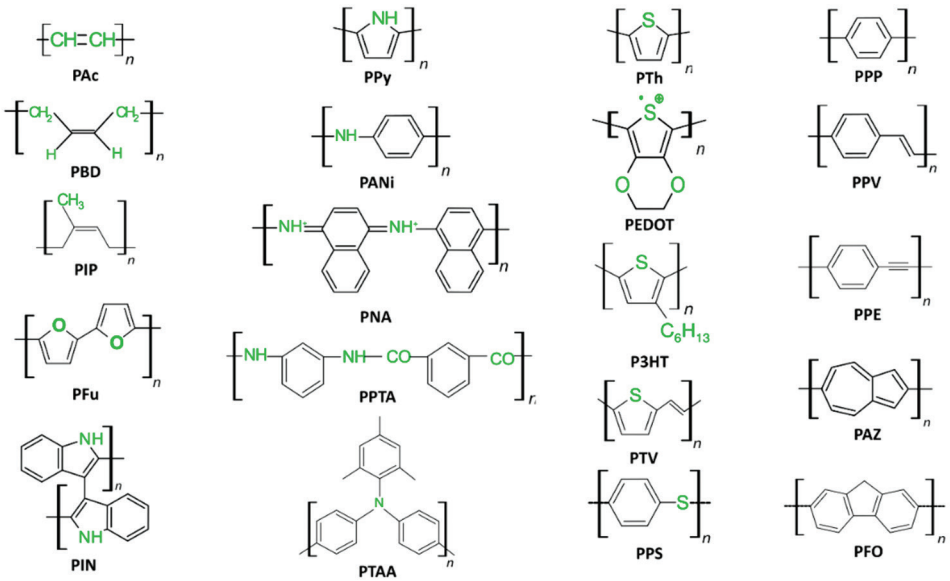

Figure 1. Inventory of conducting polymers along with their abbreviations[7]

CPs clashes with the growing demand for sustainable materials. To tackle this, researchers are looking into new ways to combine the electrical properties of CPs with the ability to break down of eco-friendly polymers. The goal is to create materials that perform well and decompose harmlessly after use. These efforts are vital for promoting sustainable biomedical technologies and cutting down on electronic waste.

2.2. Synthesis and fabrication techniques

The advancement of CPs with specific properties depends on the careful selection of synthesis and processing methods. These approaches provide precise control over material structure, conductivity, and morphology, thereby facilitating their application in transient biomedical devices. Figure 2 summarizes the three primary synthesis methods for CPs: solution-based chemical synthesis, solid-solid reaction synthesis, and electrosynthesis.

2.2.1. Solution-based chemical synthesis

Solution-based chemical synthesis is a cornerstone method for producing CPs such as PPy and PANi, widely valued for its scalability and versatility in biomedical applications. This technique employs a redox reaction where monomers with electron-donating groups are oxidized by chemical agents, generating reactive intermediates that polymerize through chain propagation or step-growth mechanisms.[9] Common oxidants, such as ammonium persulfate or ferric chloride, are cost-effective and facilitate large-scale production.[9] The method's flexibility supports integration with advanced fabrication techniques like inkjet printing, spin coating, or dip coating, enabling the creation of structured materials for biosensors, electrodes, and drug delivery systems.[10,11] Precise control over reaction conditions, particularly the oxidant-to-monomer ratio, is critical to avoid over-oxidation, which can reduce electrical conductivity.[11] Recent studies have explored innovative approaches, such as the spontaneous polymerization of pyrrole within Fe^{3+}-exchanged montmorillonite (MMT) to form intercalated PPy-MMT nanocomposites.[12] By varying the molar proportion of pyrrole to interlayer Fe^{3+}, researchers achieved tailored DC conductivity and dielectric properties, with AC conductivity following a power-law behaviour governed by correlated barrier hopping.[12] This enhances the suitability of solution-based CPs for transient biomedical devices, where controlled morphology and electrical performance are essential.

2.2.2. Electrosynthesis

Electrosynthesis offers a highly controlled approach to CP fabrication, ideal for producing thin, uniform films with customized properties. This method employs an electrochemical cell with a working electrode, counter electrode, and reference electrode immersed in a monomer-electrolyte solution. By applying a specific voltage or current, monomers undergo oxidation or reduction at the electrode surface, initiating polymerization and depositing the CP directly as a film.[13] This technique ensures high purity and allows fine-tuning of film characteristics, such as thickness, crystallinity, and conductivity, by adjusting parameters like voltage, electrolyte composition, or pH. Its single-step process eliminates the need for extensive post-processing, making it suitable for creating multilayered or patterned structures for bioelectronic interfaces.

2.2.3. Solid-solid reaction synthesis

Solid-solid reaction synthesis is a solvent-free method for fabricating CPs such as PANi and PPy, offering significant potential for biodegradable biomedical applications. This technique involves blending solid monomer powders, like

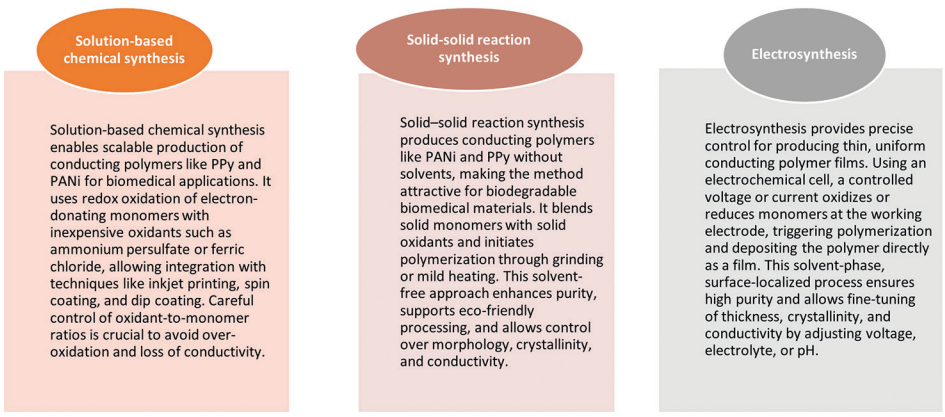

Figure 2. Different synthesis methods of conducting polymers
Abbreviations: PANi: Polyaniline; PPy: Polypyrrole.

an ilinium chloride, with solid oxidants, such as ammonium peroxydisulfate, and initiating polymerization through mechanical grinding or mild heating.[14-18] Unlike solution-based or vapor-phase methods, solid–solid synthesis relies on solid-state diffusion and surface interactions, producing high-purity polymers without solvent-related impurities, thus supporting eco-friendly manufacturing principles.[18] The method enables precise control over polymer morphology, crystallinity, and electrical conductivity by adjusting parameters such as the oxidant-to-monomer ratio and grinding duration.[17,16] For instance, PANi-MMT nanocomposites synthesized through this route exhibit a branched fibrous morphology and enhanced thermal stability compared to free PANi, attributed to the stabilizing effect of MMT's interlayer structure.[14,18] Ground MMT serves dual roles as an oxidant and reinforcement, leveraging Fe^{3+} cations in its octahedral layers and atmospheric oxygen to drive an ilinium polymerization.[5] AC conductivity studies reveal a frequency-dependent regime with low-frequency DC conductivity transitioning to a power-law behavior at higher frequencies, indicating robust electrical performance suitable for biomedical devices.[14,16,18] The solvent-free nature of this method reduces environmental impact, aligning with the demand for sustainable biomedical materials. By integrating CPs with biodegradable polymers like PLA, composites can maintain electrical functionality while degrading harmlessly in physiological environments.[1]

3. Biodegradability and transiency

3.1. Biodegradable CPs

Environmentally benign CPs are defined as polymeric materials capable of undergoing substantial degradation within a specified timeframe, ensuring that no adverse environmental impacts occur.[19,20] The term "environmentally benign" extends beyond simple mass loss or fragmentation of the CPs. A rigorous definition requires that the material and its degradation products undergo complete assimilation into natural biogeochemical cycles without leaving persistent, bioaccumulative, or toxic residues. The fate within the human body is generally favorable for the matrix components. Polyesters such as PLA and PCL undergo hydrolysis to yield metabolites such as lactic acid and caproic acid. These degradation products are efficiently cleared by the renal or metabolized through the Krebs cycle, resulting in low cytotoxicity. Similarly, natural polymers, such as chitosan and cellulose derivatives, can mineralize into carbon dioxide (CO_2) and water (H_2O), thereby minimizing environmental impact. In biomedical applications, it is crucial that the degradation products are biocompatible and can be metabolized or excreted easily by the body. When developing biodegradable CPs, it is essential to balance biodegradability with the preservation of electrical conductivity and mechanical properties inherent to CPs such as PPy and PEDOT. However, the conjugated backbone of the CP components (PPy, PEDOT, aniline oligomers) poses a greater challenge. Their degradation yields aromatic fragments, such as aniline oligomers or thiophene derivatives, could present significantly higher cytotoxicity, compared to the aliphatic acid metabolites. While these may remain below acute toxicity thresholds in controlled implants, their long-term biological impact requires careful evaluation. There are several methods for addressing the balance between biodegradability and conductivity in conducting biodegradable polymers. One of the more common methods is dispersing a conductive filler made from CP materials (e.g., PPy nanoparticles, or PEDOT nanoparticles) within a biodegradable polymer matrix (e.g., PLA and PCL). However, the presence of the conductive filler generally provides only moderate conductivity values (10^{-} to 10^{-1} S/cm) and can lead to phase separation between the filler and matrix, which can generate inconsistent electrical conductance as the PLA matrix degrades. Alternatively, there are newer potentially more precise methods which can incorporate degradable links at the molecular level. Degradable linkages, such as ester or imine groups, may be incorporated into the CP backbone to maintain π-conjugation for charge transport while also providing for controlled degradation.[21] Alternatively, hydrolyzable side groups, for example, oligoesters, can be added to CPs to maintain conductivity of the backbone while allowing for breakdown.[22] There has also been recent innovative work on more complex architectures, such as star-shaped CPs or hyperbranched CPs with degradable cores, that enhance charge transport while allowing for a more favorable disintegration profile.[23] The choice of dopants is very important for the biodegradability. Typical small-molecule dopants demonstrate little compatibility with the environment, causing researchers to transition to bio-derived dopants such as polyglutamic acid, or heparin which can serve both charge compensation and degradation pathways.[24] For instance, PEDOT doped with a modified poly (styrenesulfonate) including polyethylene glycol grafts was found to show improved biodegradability while maintaining good conductivity.[24] Characterization assesses various aspects including measurement of conductivity (e.g., via four-point probe or impedance spectroscopy), degradation kinetics through *in vitro* testing that imitates physiological or environmental conditions, and examination of mechanical properties such as tensile strength in cases of wearables or implants.[25]

4. Biomedical applications

The field of biomedical utilization and applications has rapidly progressed with CPs by incorporating conductivity, flexibility, and biocompatibility, contributing to technological advancements in healthcare.[26-41] Bio-conjugated polymers, PPy, PANi, and PEDOT, have been studied widely on their capacity to interface with biological systems, parse out electric stimuli, and detect biological signals, as well as the role in controlled degradation. New development that made strides to improve these CPs through biodegradability, developing transient devices that degrade once their purpose is served, which removes the need for surgical removal.[26,27] This section will elaborate on the various biomedical applications of biodegradable CPs, such as biosensors, tissue engineering, neural interfaces, drug delivery, and antimicrobial systems.

4.1. Biosensors for health monitoring

In biosensing applications, CPs are essential materials thanks to their high electrical conductivity, high surface area, and ability to modify the surface chemistry of CPs to achieve the right properties to isolate/deploy the biological analyte of interest.[26] As shown in Figure 3, the role of CPs is significant as they are responsible for changing a certain type of input stimulus into an electrical signal in monitoring health. The illustration in Figure 3 breaks the process into three pathways based on the type of signal: Chemical, electrochemical, or mechanical. The first pathway is activated by a biochemical signal, such as a protein or DNA, and illustrates how CPs can stimulate this signal. A biological receptor which is functionalized with a "bio-factor" will bind to the analyte (signal), and the CP will emit a signal, transmitting the signal to the processing unit. For electrochemical-type signals, such as heat or pH, CPs can either directly record the signal, or the CPs can be modified to enhance the reception of the signal. CPs could also be modified to act as a transducer for electrochemical signals. Finally, for mechanical signals, such as pressure or vibration, CPs will transduce the physical force into electrical signal. In all examples, the CP-based device will be connected to a signal unit for independent signal processing or for use as a part of a data set. The figure visually summarizes how CPs act as an active and flexible constituent in the biosensor designs.[26]

The aforementioned quality makes CPs (e.g., PPy and PEDOT) favorable for developing sensors for continuous glucose monitoring, lactate detection, and cardiac biomarker analysis (human troponin) classifiers for diabetes management, sports performance monitoring, and heart health assessment.[26] For instance, PPy-based biosensors have been incorporated into a wearable sensor for real-time glucose monitoring with high sensitivity and flexibility.[26] Similarly, both PEDOT-based DNA sensors and biochips have taken advantage of PPy's capacity to functionalize surfaces with biomolecules to achieve highly specific detection of genetic material or pathogens.[26] Recent studies have advanced CP-based biosensors through the addition of components that lead to biodegradability. For example, PPy-dextrin (*in situ*) nanocomposites have antibacterial and antioxidant properties, and can also be useful in infection monitoring sensors.[30] These composites demonstrate conductivity (up to 10^{-3} S/cm) and biodegradability.[30] Furthermore, researchers have experienced highly sensitive CP-based biosensors through the addition of components, such as carbon nanotubes or silver nanoparticles.[26,33] For example, PPy combined with multi-walled carbon nanotubes (MWCNTs) in biodegradable poly(L-lactide)/poly(3-hydroxybutyrate-co-4-hydroxybutyrate) blends

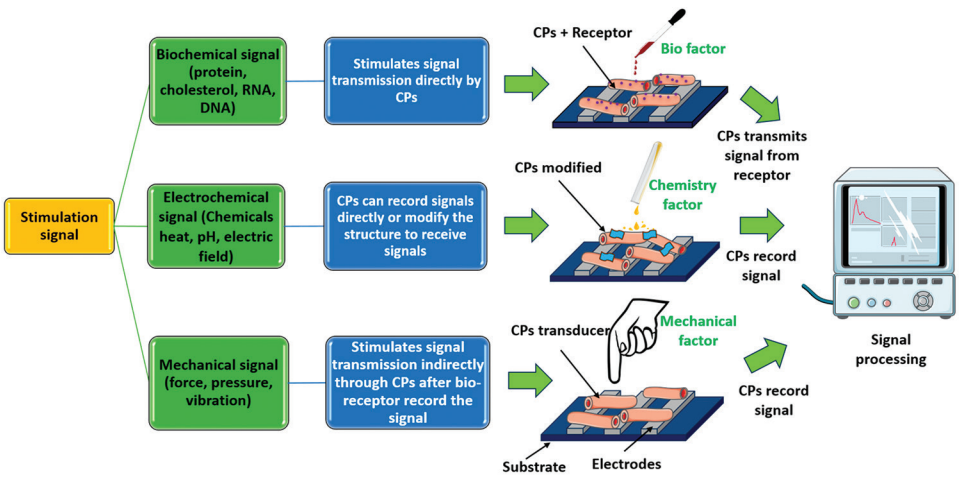

Figure 3. The role of conducting polymers in receiving and processing stimulation signals[7]

achieved a very low percolation threshold (0.58 wt%),which is crucial for conductivity improvements.[36]

4.2. Tissue engineering and regeneration

CPs are widely used in tissue engineering, especially for neural, cardiac, and bladder tissue regrowth, to apply electrical stimulation to facilitate cell growth, cell adhesion and cell differentiation.[26,27] For example, a biodegradable PEDOT-poly(octamethylene-citrate-co-octanol) scaffold was developed for bladder tissue regeneration in athymic rats.[27] This electroactive scaffold reinstated bladder function, and anatomical structure, without the use of exogenous cell seeding, comparable to scaffolds seeded with mesenchymal stromal cell, demonstrating the ability of biodegradable scaffolds without cells.[27] The scaffold conductivity with ~10^{-5} S/cm and degradability allows temporary mechanical property support for non-conductive tissue scaffolds, then degrades into innocuous products once bladder regeneration is complete.[27] In the same context, PPy-chitosan composites increase Schwann cell proliferation, and secretion of neurotrophins, such as nerve growth factor (NGF) and the brain-derived neurotrophic factor (BDNF), upon the application of electrical stimulation.[31] *In vitro* experimentation demonstrated that electrical stimulation through PPy-chitosan scaffolds greatly increased expression of NGF and BDNF, and improved peripheral nerve regeneration in animal models.[31] Synthesized with aniline trimer and doped with camphor sulfonic acid, biodegradable conductive polyurethanes have an elasticity of 30% strain and a conductivity of up to 7.3×10^{-5} S/cm in wet state, and promote fibroblast proliferation, which is important for tissue repair.[29] All of these materials biodegrade into non-toxic byproducts to minimize inflammatory responses and offer advantages for implantation, such as liquidation after degradation. Furthermore, PCL-based scaffolds with conductive fillers such as MWCNTs provide mechanical strength and biocompatibility to promote both bone and cartilage regeneration.[32] The micropatterned surface of these scaffolds drives stem cell differentiation and improves the integration of engineered tissues.[32] In another study, Subramanian *et al.*[42] produced aligned nanofibers of poly(lactic-co-glycolic acid)/poly(3-hexylthiophene)to promote Schwann cell alignment and myelin formation and to aid peripheral nerve repair in rodent models. Xu *et al.*[43] created PEDOT/carboxymethyl chitosan hydrogels to address cranial injury. Huang *et al.*,[44] studied the use of PLA-b-aniline pentamer-b-PLA (PAP) (5×10^{-6} S/cm) to synchronize cardiomyocyte beating for increasing junction formation and contractile force in damaged hearts. Baheiraei *et al.*[45] described electroactive polyurethane scaffolds that restored conduction velocity in disrupted myocardium (but risked arrhythmia). Xie *et al.*,[46] elucidated star polylactide-aniline trimer networks to improve osteoblast mineralization and collagen deposition, leading to 80% defect closure in femoral models.

4.3. Neural interfaces and stimulation

CPs play a key role in neural interfaces due to their unique ability to interface with neural tissue and provide an ability to deliver controlled electrical stimulation to live tissue, allowing neural recording and stimulation. Biodegradable magnesium-based microelectrodes decorated with PEDOT have also been developed specifically for *in vivo* neural recording in the auditory cortex of mice, recording multi-unit stimulus-evoked activity from the brain.[34] These microelectrodes utilize biodegradable polymers for insulation, which will degrade within a safe amount of time after implantation, avoiding the downsides to chronic implantation.[34] In addition, PEDOT has a conductivity of ~10^{-4} S/cm, enabling reliable signal acquisition, making PEDOT suitable for transient neural interfaces.[34] Furthermore, in peripheral nerve repair, a conductive hydrogel integrating polydopamine-modified silicon phosphorus (SiP@PDA) nanosheets in a gelatin methacryloyl matrix promoted differentiation of neural stem cells into Schwann cell-like cells.[28] This hydrogel has a conductivity of ~4.34 mS/cm and has properties comparable to those of neural tissue, causing resident macrophages to polarize toward a pro-healing phenotype, enhancing tissue angiogenesis.[28] In a rat model of Parkinson's disease, this hydrogel combined with acupuncture induced a more than 80% increase in the regeneration of dopaminergic neurons and improved motor function with the electrophysiological spike rates returning to levels comparable to those of healthy rats.[28] Since the scaffolds are biodegradable, complications related to their long-term use owing to non-degradation can be prevented.[28] In addition, polyphosphazene polymers with aniline pentamer side chains also provide a combination of conductivity (~2×10^{-5} S/cm) and biodegradability, which are the characteristics required in neuronal tissue engineering.

4.4. Biomedical implants

For long-lasting implants, materials must exhibit mechanical strength, electrical functionality, and the ability to controllably resorb to prevent secondary surgical interventions. Boutry *et al.*[47] created PPy and PCL-PPy RLC resonators through emulsion polymerization to allow for wireless bioelectronic implants. Both poly(L-lactic acid) (PLLA) and PCL degrade through hydrolytic chain scission into lactic and caproic acid, respectively, which are metabolites capable of elimination by the body through the

Krebs cycle. Lu *et al.*[48] developed PPy/hybrid electrodes for neural probes, where PPy provided the conductivity, and carbon nanotubes aided in mechanical stability; however, full evaluation of the long-term degradation was not provided. For orthopedic application, Wan *et al.*[49] incorporated magnesium into the PLLA forming PLLA/Mg/MgF_2 composites. The released magnesium ions supported osteogenic pathways while PLLA degraded through hydrolysis over the period of 6–12 months. In a separate study, Ghaziof and Mehdikhani-Nahrkhalaji[50] fabricated1 wt% MWCNT/PCL scaffolds using solvent casting and vacuum drying methods, which significantly improved electrical conductivity and compressive strength for myocardial patches; however, the degradation of the PCL matrix was relatively slow and appropriate for load-bearing cardiac repair. Similarly, Wang *et al.*[51] developed nano-Fe_3O_4/PLLA bone screws, which introduced magnetic guidance and were biodegradable. The degradation of the PLLA was accelerated by acidic byproducts, where Fe_3O_4 was included to promote radiopacity. Jiang *et al.*[52] electro spun PCL/gelatin/carbon nanotubes vascular grafts that mimic native vessel mechanics. The gelatin component rapidly degraded via enzymatic action, while PCL provided long-term structural support through gradual hydrolysis.

4.5. Drug delivery and antimicrobial applications

CPs enable precise drug delivery through electrical or environmental stimuli, thereby enhancing therapeutic outcomes. A biodegradable, electroconductive self-healing hydrogel based on polydopamine-coated polyurethane nanoparticles supports neural stem cell proliferation and differentiation, with strong antioxidative and anti-inflammatory effects.[28] This hydrogel, used in a Parkinson's disease model, elevated serum levels transforming growth factor-β1 and stromal cell-derived factor-1, promoting neuroprotection and reducing inflammation.[28] Its conductivity (~4.34 mS/cm) and shear modulus (~280 Pa) mimic brain tissue, making it ideal for injectable drug delivery systems.[28] CPs also exhibit antimicrobial properties, critical for infection-resistant biomedical devices. PPy-dextrin nanocomposites demonstrate antibacterial activity against Gram-positive (e.g., *Staphylococcus aureus*) and Gram-negative (e.g., *Pseudomonas aeruginosa*) bacteria, suitable for wound dressings or implants.[30] Ultrathin electro spun mats combining PCL, silver nitrate, and carboxymethyl chitosan offer high antibacterial efficacy, breathability, and biodegradability, making them effective face mask filters for airborne disease prevention.[33] These mats, with a total thickness of ~300 μm, provide mechanical stability and degrade naturally, reducing environmental impact.[33] Similarly, electrostatically flocked PCL microfibers filled with silver nanoparticles exhibit antimicrobial activity against methicillin-resistant *S. aureus*, supporting tissue formation and vascularization *in vivo*.[37] Sumitha *et al.*[53] electro spun PCL/silver nanofibrous scaffolds, showing a clear zone of inhibition against *S. aureus* proportional to Ag content. PCL degraded through hydrolysis, enabling sustained Ag^+ release.

4.6. Biodegradable electroactive scaffolds

The integration of biodegradability into CP-based systems has opened new avenues for transient biomedical devices. For example, PPy grafted with oligo-3-hydroxybutyrate pendants combines conductivity with biodegradability, suitable for temporary scaffolds in tissue engineering.[38] Electrostatic flocking of silver nanoparticle-filled PCL microfibers creates biphasic scaffolds that degrade naturally while promoting new tissue formation and angiogenesis.[37] Cataractous eye protein isolate -based solid polymer electrolytes achieve high ionic conductivity (~8×10^{-a} S/cm) and biodegradability, offering potential for flexible bioelectronics.[39] These materials leverage natural proteins, enhancing sustainability and biocompatibility.[39] CPs blended with biodegradable polymers, such as PLA or polybutylene succinate, form conductive foams for neural recording or energy storage.[40] Polybutylene succinate-based foams with carbon nanofibers and expanded graphite achieve tailored cellular structures, supporting biomedical applications.[40] In addition, novel CPs with degradable ester linkages, such as quarter thiophene-ester polymers, exhibit electroactivity and cytocompatibility, which are ideal for tissue-engineering scaffolds.[41] These advancements underscore the potential of biodegradable CPs in creating sustainable, high-performance biomedical devices.

5. Synthesis strategy

Chemical precision, structural control, and biocompatibility are critical aspects to consider in the synthesis of biodegradable, electroactive CP-based composites. Condensation polymerization is the cornerstone for block copolymers with controlled degradation. Huang *et al.*[44] synthesized polylactide-block-aniline pentamer-block-polylactide by condensing polylactide diols with aniline pentamer through carbodiimide coupling, yielding a triblock structure with microphase separation and conductivity of 5×10^{-6} siemens per centimeter. Similarly, Rivers *et al.*[54] employed a multi-step condensation sequence—trichloro acetylation, Vilsmeier-Haack formylation, Stetter reaction, Lawesson's thionation, hydrolysis, and adipoyl chloride linkage—to construct a pyrrole-thiophene-pyrrole trimer with ester-linked aliphatic chains, enabling enzymatic surface erosion. Electro spinning dominates nanofibrous scaffold fabrication. Subramanian *et al.*[42] dissolved

poly(lactic-co-glycolic acid) and poly(3-hexylthiophene) in chloroform/dimethylformamide, electrospinning aligned nanofibers under 15 kV to promote Schwann cell orientation. Jiang *et al.*[52] co-electro spun PCL/gelatin/carbon nanotube blends, achieving vascular grafts with native-like mechanics. High-voltage fields induce fiber alignment, enhancing conductivity pathways and cell guidance. Oxidative polymerization enables *in situ* growth of CPs on biodegradable templates. Da Silva *et al.*[55] polymerized PEDOT-copolymer-poly(D,L-lactide) using ammonium persulfate in aqueous media, forming a biodegradable, electroactive copolymer. Boutry *et al.*[47] used emulsion polymerization to coat PLLA/PCL with PPy, forming resistor–inductor–capacitor resonators. Ghaziof *et al.*[50] applied solvent casting with vacuum drying to integrate 1 wt% MWCNTs into PCL, improving conductivity for myocardial patches. These methods—condensation, electrospinning, oxidative/electrochemical polymerization, and emulsion/solvent processing—allow tunable conductivity, porosity, and degradation kinetics, making biodegradable CP-based composites versatile for tissue engineering, implants, and antibacterial therapy.

6. Mechanism of degradation

Degradation of biodegradable CP-based composites is a multistage process governed by chemical structure, environmental conditions, and biological activity. As shown in Figure 4, there are three primary mechanisms of degradation—namely hydrolytic degradation, enzymatic degradation, and surface erosion—each tailored to ensure controlled resorption, non-toxic byproducts, and preserved electroactivity during tissue integration. Hydrolytic degradation dominates polyester-based systems (PLLA, PCL, poly(lactic-co-glycolic acid), poly(D,L-lactide)).

Ester bonds in the polymer backbone undergo nucleophilic attack by water, leading to chain scission and formation of carboxylic acid and alcohol end groups. Huang *et al.*[44] reported polylactide-block-aniline pentamer-block-polylactide degrading through bulk hydrolysis of polylactide blocks, releasing lactic acid over 6–12 months. Subramanian *et al.*[42] observed poly(lactic-co-glycolic acid)/poly(3-hexylthiophene) nanofibers losing 50% mass in 30 days under phosphate-buffered saline immersion, with autocatalysis accelerating degradation as acidic byproducts accumulate. PCL-based implants exhibit slower hydrolysis (lasting 1–2 years), making them ideal for long-term vascular or myocardial support.[50,52] Hydrolysis is pH-, temperature-, and molecular weight-dependent, enabling tunable resorption rates. Enzymatic degradation is critical in polysaccharide-containing composites (chitosan, chitin, carboxymethyl chitosan), comprising 25% of entries. Lysozyme, chitinase, and chitosanase—abundant in human serum and wound exudate—cleave beta-1,4-glycosidic bonds, generating oligosaccharides. Xu *et al.*[43] demonstrated PEDOT/carboxymethyl chitosan hydrogels degrading faster in lysozyme-rich media than phosphate-buffered saline, with surface-limited erosion preserving

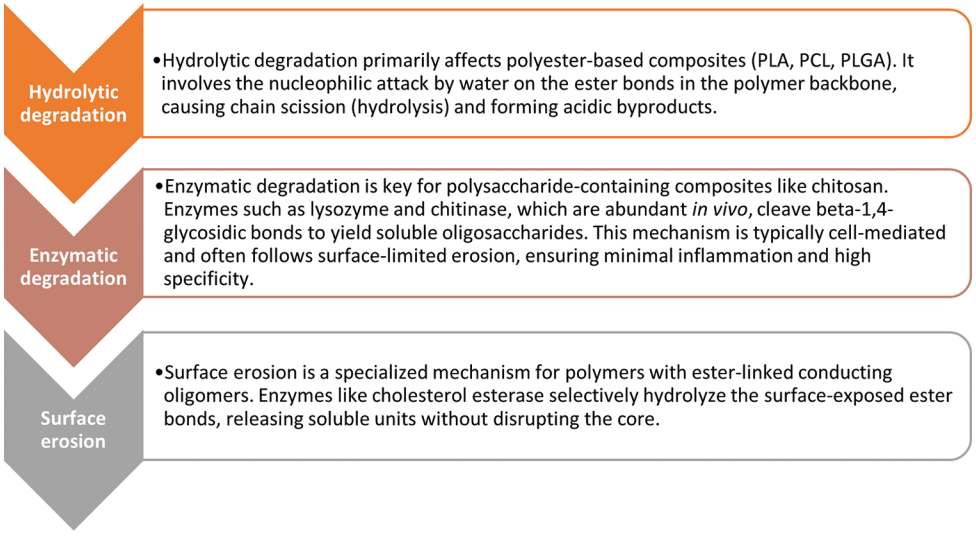

Figure 4. Principle mechanisms of degradation of conducting polymers

bulk conductivity. Enzymatic pathways are cell-mediated, ensuring *in vivo* specificity and minimal inflammation. Surface erosion, unique to CP oligomers, occurs in ester-linked systems like biodegradable electrically CP.[54] Cholesterol esterase selectively hydrolyzes surface-exposed ester linkages, releasing soluble monomers while maintaining core integrity. This mechanism yields zero-order kinetics, ideal for drug delivery or transient neural scaffolds, with conductivity retained until late-stage erosion. These mechanisms—hydrolytic (bulk/surface), enzymatic, and erosive—enable predictable, safe degradation, transforming biodegradable CP-based composites into transient, bioactive platforms for regenerative medicine. It is important to note that for biodegradable CPs, degradability is engineered through strategically placed hydrolyzable (e.g., ester, imine) or enzymatically cleavable (e.g., peptide, glycosidic) segments that preserve π-conjugation and charge mobility during the functional phase, enabling controlled fragmentation only on physiological or environmental triggers.[21,38,44] A fundamental challenge in designing functional biodegradable CPs is managing the inherent conflict between electrical performance and material biodegradability. Conductivity relies on a stable, continuous network of π-conjugated segments to facilitate charge transport. Biodegradability, however, requires controlled, bulk breakdown of the polymer backbone through hydrolyzable linkages. The universal observation is that conductivity is negatively impacted by biodegradation, though the performance can be sustained for a functional period. This makes biodegradable CPs inherently transient materials, whose electrical function must be strategically designed to outlast the duration of the biological application (e.g., nerve regeneration or cardiac repair) before the material fully dissolves. For instance, PAP triblock copolymer is achieved by ingeniously linking distinct functional segments, while their degradation capability stems from separate, chemically labile units.[44] The material's semiconducting performance (5×10^{-6} S/cm) is conferred by the π-conjugated backbone of the aniline pentamer oligomer, which, upon doping, forms mobile charge carriers, polarons and bipolarons, that facilitate electron hopping or tunneling for charge transport. Conversely, biodegradability is engineered through the polylactide segments containing hydrolyzable ester linkages. This morphology permits the polylactide to degrade via hydrolysis without immediately disrupting the conductive pathways, sustaining function during the necessary biological window. However, this is an inherently transient solution, as the inevitable progression of degradation—involving polymer swelling, dopant expulsion, and eventual chain fragmentation—ultimately severs the conjugation. This failure mechanism leads to a significant, unavoidable drop in conductivity (>50%).[44]

7. Comparative analysis of synthesis, degradation, and applications

To provide a comprehensive overview of the diverse biodegradable CP-based composites discussed in this review, Table 1 summarizes key attributes from some selected studies across tissue engineering, biomedical implants, and antibacterial applications. This table compiles essential parameters, including polymer/composite type, conducting component, dopant, synthesis method, degradation mechanism, conductivity, and primary application. Our tabulated data reveal that condensation polymerization and electrospinning are primary methods for synthesizing scaffolds requiring precise molecular control and nanofibrous alignment, respectively, while oxidative and emulsion techniques are predominantly employed in generating implant-focused hybrids for enhanced mechanical integration. Degradation profiles, primarily hydrolytic or enzymatic, ensure controlled release of non-toxic byproducts, aligning with clinical needs for transient devices.

8. Challenges and future directions

Despite their promise, CP-based biomedical devices face challenges in balancing conductivity with degradation rates. Rapid degradation can compromise functionality, while high conductivity often requires stable, non-degradable structures.[26,28] Scalability is another hurdle, as complex synthesis routes, such as those involving organic solvents, limit large-scale production.[27,30] The lack of standardized protocols for assessing biodegradability and biocompatibility across physiological and environmental conditions necessitates universal benchmarks.[26] In addition, achieving consistent mechanical properties, such as flexibility and tensile strength, remains critical for wearable and implantable devices.[32] Future research will focus on developing novel synthesis methods, such as solid-state polymerization, to enhance eco-friendliness and scalability.[30] Incorporating stimuli-responsive triggers (e.g., pH, light, or enzymes) will enable smarter, more precise devices.[28,33] Integration with advanced nanomaterials, like graphene or quantum dots, will further enhance conductivity and functionality.[26] Applications in transient electronics, smart drug delivery, and wearable sensors hold significant potential, particularly for personalized medicine and sustainable healthcare.[26,28] By addressing these challenges, biodegradable CPs will drive the development of next-generation biomedical technologies, combining high performance with environmental responsibility.

Table 1. Composition, synthesis methods, degradation mechanisms, electrical conductivity, and biomedical applications of biodegradable conducting polymers

Polymer or composite	Electricallyconductive component	Dopant	Synthesis method	Degradation mechanism	Electrical conductivity (S/cm)	Application	References
Pyrrole–thiophene–pyrrole trimer	Pyrrole–thiophene–pyrrole trimer	Iodine vapor	Multi-stepchemical condensation process	Enzymatic degradation by cholesterol esterase	10^{-4}	Neural tissue scaffold	54
Polylactide–aniline pentamer–polylactide block copolymer	Aniline pentamer	-	Condensation	Hydrolysis of polylactide chains	5×10^{-6}	Cardiac and brain tissue engineering	44
Poly (lactic-co-glycolic acid) and poly (3-hexylthiophene) nanofibers	Poly (3-hexylthiophene)	-	Electrospinningprocess	Hydrolysis of poly (lactic-co-glycolic acid)	-	Neural tissue regeneration	42
Electroactive polyurethane incorporating aniline pentamer	Aniline pentamer	-	Synthesis of electroactive polyurethane	Hydrolytic and enzymatic degradation	-	Cardiac and bone tissue engineering	45
Star-shaped polylactide network with aniline trimer	Aniline trimer	-	Formation of star-shaped polymer network	Controlled hydrolysis	-	Bone tissue engineering	46
3Dreducedgraphene oxide/PPy/hydroxyapatite composite scaffold	PPy	-	Room-temperature chemical fabrication	-	-	Bone tissue engineering	56
PPyand alginate hybrid hydrogel	PPy	-	Hybridhydrogel fabrication	Hydrolysis of alginate	-	Brain tissue engineering and human mesenchymal stem cell culture	57
PEDOT-co-poly (D, L-lactide) copolymer	PEDOT	Persulfate oxidizing agent	Oxidativepolymerization	Hydrolysis of poly (D, L-lactide)	-	Embryonicstem cell compatibility	55
PEDOT/carboxymethyl chitosan hydrogel	PEDOT	-	Composite hydrogel fabrication	Hydrolytic and enzymatic degradation	-	Neural tissue engineering	43
PANi–chitosanfunctionalizednanocomposite	PANi	-	N-hydroxysuccinimide modification and polymergrafting	Enzymatic degradation	-	Fibroblastapplications	58
PLLA-PPy and PCL-PPycomposites	PPy	-	Emulsion-based composite fabrication	Hydrolysis of PLLA or PCL	-	Bioelectronicresonatordevices	47
PPy/carbon nanotube composite film	PPy	-	Hybridchemical/electrodeposition fabrication	-	-	Neural interface electrodes	48
MWCNT-Reinforced Polycaprolactone Nanocomposite	MWCNTs	-	Solvent casting technique	Hydrolysis of polycaprolactone	Improved compared to pure polycaprolactone	Myocardialtissue engineering	50
PLL Acomposite bone screw with nano-sized iron oxide (magnetite)	Nano iron oxide (Fe_3O_4)	-	Composite bone screw fabrication	Hydrolysis of PLLA	-	Bone screw implant	51
3Dscaffold based on PEDOT: polystyrenesulfonate and MWCNTs	PEDOT: polystyrene sulfonate and MWCNTs	-	3Dcomposite scaffold fabrication	-	-	Biosensingapplications	59

(Cont'd...)

Table 1. ***(Continued)***

Polymer or composite	Electricallyconductive component	Dopant	Synthesis method	Degradation mechanism	Electrical conductivity (S/cm)	Application	References
Poly (3-hydroxybutyrate)/chitosan/ MWCNT electro spun scaffold	MWCNTs	-	Solution blending and electro spinning	Hydrolytic and enzymatic degradation	-	Cartilage tissue engineering	60
PPy/zinc oxide composite coating on biodegradable magnesiumalloy	PPy	-	Composite coating deposition	-	-	Orthopedicimplant coating	61

Abbreviations: MWCNT: Multi-walled carbon nanotubes; PANi: Polyaniline; PCL: Poly(ε-caprolactone); PEDOT: Poly (3,4-ethylenedioxythiophene); PLLA: Poly (L-lactic acid); PPy: Polypyrrole.

9. Conclusion

Biodegradable CPs represent a significant leap forward in the field of biomedical materials, offering a compelling solution to the long-standing challenges of permanent electronic implants and biomedical waste. This review highlights how these innovative materials uniquely combine electrical conductivity, biocompatibility, and controlled degradability to create a new generation of transient medical devices. In addition, the paper discusses the diverse and impactful applications of these materials, from biosensors for real-time health monitoring and electroactive scaffolds that enhance tissue regeneration, to neural interfaces that enable communication with the nervous system and smart systems for targeted drug delivery. The review also examines the synthesis and fabrication methods—including chemical oxidative, electrosynthesis, and solid–solid reactions—that allow for precise control over material properties, a critical factor for clinical success. Despite these remarkable advancements, significant hurdles remain. The key challenge lies in achieving an optimal balance between electrical performance and degradation rate so that the device functions effectively as required and then degrades safely. Issues related to scalability, standardization of testing protocols, and maintaining consistent mechanical properties also require further research. Looking ahead, the future of biodegradable CPs is incredibly promising. Continued innovation in stimuli-responsive degradation, the integration of advanced nanomaterials, and the development of more sustainable fabrication techniques will pave the way for a new era of personalized and eco-friendly medicine. By overcoming these challenges, biodegradable CPs are set to revolutionize healthcare by enabling devices that are not only high-performing but also fully integrated with the body's natural processes.

Acknowledgments

The authors would like to thank the Tunisian Ministry of Higher Education and Scientific Research for funding this research.

Funding

The authors gratefully acknowledge the financial support provided by the Ministry of Higher Education and Scientific Research of Tunisia (MESRS).

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: All authors
Visualization: Imene Bekri-Abbes

Writing–original draft: All authors
Writing–review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

References

1. Scott C. History of conductive polymers. In: *Nanostructured Conductive Polymers*. Chichester: John Wiley and Sons; 2010. p. 1-34.

   doi: 10.1002/9780470661338.ch1

2. Kenry, Liu B. Recent advances in biodegradable conducting polymers and their biomedical applications. *Biomacromolecules*. 2018;19(6):1783-1799.

   doi: 10.1021/acs.biomac.8b00275

3. Khan T, Vadivel G, Ramasamy B, Murugesan G, Sebaey TA. Biodegradable conducting polymer-based composites for biomedical applications-a review. *Polymers (Basel)*. 2024;16(11):1533.

   doi: 10.3390/polym16111533

4. Hasan MB, Parvez MM, Abir AY, Ahmad MF. A review on conducting organic polymers: Concepts, applications, and potential environmental benefits. *Heliyon*. 2025;11(3):e42375.

   doi: 10.1016/j.heliyon.2025.e42375

5. Nezakati T, Seifalian A, Tan A, Seifalian AM. Conductive polymers: Opportunities and challenges in biomedical applications. *Chem Rev*. 2018;118(14):6766-6784.

   doi: 10.1021/acs.chemrev.6b00275

6. Namsheer K, Rout CS. Conducting polymers: A comprehensive review on recent advances in synthesis, properties and applications. *RSC Adv*. 2021;11(10):5659-5691.

   doi: 10.1039/d0ra07800j

7. Le CV, Yoon H. Advances in the use of conducting polymers for healthcare monitoring. *Int J Mol Sci*. 2024;25(3):1564.

   doi: 10.3390/ijms25031564.10.3390/ijms25031564

8. Tadesse MG, Ahmmed AS, Lübben JF. Review on conductive polymer composites for supercapacitor applications. *J Compos Sci*. 2024;8(2):53.

   doi: 10.3390/jcs8020053

9. Bednarczyk K, Matysiak W, Tański T, Janeczek H, Schab-Balcerzak E, Libera M. Effect of polyaniline content and protonating dopants on electroconductive composites. *Sci Rep*. 2021;11(1):7487.

   doi: 10.1038/s41598-021-86950-4

10. Arora EK, Sharma V, Ravi A, *et al*. Polyaniline-based ink for inkjet printing for supercapacitors, sensors, and electrochromic devices. *Energies*. 2023;16(18):6716.

    doi: 10.3390/en16186716

11. Kaushik P, Bharti R, Sharma R, Verma M, Olsson RT, Pandey A. Progress in synthesis and applications of polyaniline-coated nanocomposites: A comprehensive review. *Eur Polym J*. 2024;221:113574.

    doi: 10.1016/j.eurpolymj.2024.113574

12. Zidi R, Bekri-Abbes I, Sdiri N, Vimalanandan A, Rohwerder M, Srasra E. Electrical and dielectric investigation of intercalated polypyrrole-montmorillonite nanocomposite prepared by spontaneous polymerization. *Mater Sci Eng B*. 2016;212:14-23.

    doi: 10.1016/j.mseb.2016.07.006

13. Li C, Bai H, Shi G. Conducting polymer nanomaterials: Electrosynthesis and applications. *Chem Soc Rev*. 2009;38(8):2417-2427.

    doi: 10.1039/b816681c

14. Bekri-Abbes IB, Srasra E. Characterization and AC conductivity of polyaniline-montmorillonite nanocomposites synthesized by mechanical/chemical reaction. *React Funct Polym*. 2010;70(1):11-18.

    doi: 10.1016/j.reactfunctpolym.2009.09.008

15. Bekri-Abbes I, Srasra E. Effect of mechanochemical treatment on structure and electrical properties of montmorillonite. *J Alloys Compd*. 2016;671:34-42.

    doi: 10.1016/j.jallcom.2016.02.048

16. Bekri-Abbes I, Srasra E. Solid-State synthesis and electrical properties of polyaniline/Cu-montmorillonite nanocomposite. *Mater Res Bull*. 2010;45(12):1941-1947.

    doi: 10.1016/j.materresbull.2010.08.012

17. Bekri-Abbes I, Srasra E. Investigation of structure and conductivity properties of polyaniline synthesized by solid-solid reaction. *J Polym Res*. 2011;18(4):659-665.

    doi: 10.1007/s10965-010-9461-x

18. Bekri-Abbes I, Srasra E. Solid phase mechanochemical synthesis of polyaniline-montmorillonite nanocomposite using grinded montmorillonite as oxidant. *Mater Sci Semicond Process*. 2016;56:76-82.

    doi: 10.1016/j.mssp.2016.07.020

19. Gu JD, Wu EK. Biodegradability of synthetic plastics and polymeric materials: An illusion or reality in waste managements? *Appl Environ Biotechnol*. 2020;5(2):9-27.

doi: 10.26789/AEB.2020.02.003

20. ASTM International. *ASTM D6691-24a: Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment*. West Conshohocken, PA: ASTM International; 2024.

21. Kuperkar K, Atanase LI, Bahadur A, Crivei IC, Bahadur P. Degradable polymeric bio(nano)materials and their biomedical applications: A comprehensive overview and recent updates. *Polymers (Basel)*. 2024;16(2):206.

doi: 10.3390/polym16020206

22. Jia X, Ma X, Zhao L, *et al*. A biocompatible and fully erodible conducting polymer enables implanted rechargeable Zn batteries. *Chem Sci*. 2023;14(9):2123-2130.

doi: 10.1039/d2sc06342e

23. Guo B, Finne-Wistrand A, Albertsson AC. Enhanced electrical conductivity by macromolecular architecture: Hyperbranched electroactive and degradable block copolymers based on poly(ε-caprolactone) and aniline pentamer. *Macromolecules*. 2010;43(10):4472-4480.

doi: 10.1021/ma100530k

24. Gupta S, Datt R, Mishra A, Tsoi WC, Patra A, Bober P. Poly(3,4-ethylenedioxythiophene):Poly(styrene sulfonate) in antibacterial, tissue engineering and biosensors applications: Progress, challenges and perspectives. *J Appl Polym Sci*. 2022;139(30):e52663.

doi: 10.1002/app.52663

25. Najar Benahmed W, Bekri-Abbes I, Srasra E. Spectroscopic study of polyaniline/AgCl@Ag nanocomposites prepared by a one-step method. *J Spectrosc*. 2017;2017:3514216.

doi: 10.1155/2018/7320654

26. Irimia-Vladu M. "Green" electronics: Biodegradable and biocompatible materials and devices for sustainable future. *Chem Soc Rev*. 2014;43(2):588-610.

doi: 10.1039/C3CS60235D

27. Keate RL, Bury MI, Mendez-Santos M, *et al*. Cell-free biodegradable electroactive scaffold for urinary bladder tissue regeneration. *Nat Commun*. 2025;16(1):11.

doi: 10.1038/s41467-024-55401-9

28. Chen TY, Xu J, Tai CH, Wen TK, Hsu SH. Biodegradable, electroconductive self-healing hydrogel based on polydopamine-coated polyurethane nano-crosslinker for Parkinson's disease therapy. *Biomaterials*. 2025;320:123268.

doi: 10.1016/j.biomaterials.2025.123268

29. Xu C, Yepez G, Wei Z, Bugarin A, Hong Y. Synthesis and characterization of conductive, biodegradable, elastomeric polyurethanes for biomedical applications. *J Biomed Mater Res A*. 2016;104(9):2305-2314.

doi: 10.1002/jbm.a.35765

30. Nazarzadeh Zare E, Mansour Lakouraj M, Mohseni M. Biodegradable polypyrrole/dextrin conductive nanocomposite: Synthesis, characterization, antioxidant and antibacterial activity. *Synth Met*. 2014;187:9-16.

doi: 10.1016/j.synthmet.2013.09.045

31. Huang J, Hu X, Lu L, Zhang Q, Luo Z. Electrical regulation of Schwann cells using conductive polypyrrole/chitosan polymers. *J Biomed Mater Res A*. 2010;93(1):164-174.

doi: 10.1002/jbm.a.32511

32. Golubchikov DO, Petrov AK, Popkov VA, Evdokimov PV, Putlayev VI. Recent advances on 3D-printed PCL-based composite scaffolds for bone tissue engineering. *ACS Biomater Sci Eng*. 2025;11(6):3201-3327.

doi: 10.3389/fbioe.2023.1168504

33. Ganguly K, Randhawa A, Dutta SD, *et al*. Ultrathin, stimuli-responsive, antimicrobial, self-cleaning, reusable, and biodegradable, micro/nanofibrous electrospun mat as an efficient face mask filter for airborne disease prevention. *Nano Lett*. 2025;25(19):7641-7650.

doi: 10.1021/acs.nanolett.4c04525

34. Zhang X, Liu B, Gao J, *et al*. Liquid metal-based electrode array for neural signal recording. *Bioengineering (Basel)*. 2023;10(5):578.

doi: 10.3390/bioengineering10050578

35. Zhang Q, Yan Y, Li S, Feng T. The synthesis and characterization of a novel biodegradable and electroactive polyphosphazene for nerve regeneration. *Mater Sci Eng C Mater Biol Appl*. 2010;30(1):160-166.

doi: 10.1016/j.msec.2009.09.013

36. Hu K, Huang D, Jiang H, *et al*. Toughening biosourced poly(lactic acid) and poly(3-hydroxybutyrate-co-4-hydroxybutyrate) blends by a renewable poly(epichlorohydrin-co-ethylene oxide) elastomer. *ACS Omega*. 2019;4(22):19777-19786.

doi: 10.1021/acsomega.9b02639

37. McCarthy A, John JV, Saldana L, *et al*. Electrostatic flocking of insulative and biodegradable polymer microfibers for biomedical applications. *Adv Healthc Mater*. 2021;10(19):2100766.

doi: 10.1002/adhm.202100766

38. Domagala A, Maksymiak M, Janeczek H, *et al*. Oligo-3-hydroxybutyrate functionalised pyrroles for preparation of biodegradable conductive polymers. *J Mater Sci*. 2014;49(14):5227-5236.

doi: 10.1007/s10853-014-8241-0

39. Chowdhury P, Lincon A, Bhowmik S, *et al*. Biodegradable solid polymer electrolytes from the discarded cataractous eye protein isolate. *ACS Appl Bio Mater*. 2024;7(4):2240-2253.

doi: 10.1021/acsabm.3c01229

40. Cafiero L, Oliviero M, Landi G, *et al*. Preparation and characterization of conductive foams based on PBS, carbon nanofibers and expanded graphite nanocomposites. *AIP Conf Proc*. 2017;1914:060006.

doi: 10.1063/1.5016726

41. Guimard NK, Sessler JL, Schmidt CE. Design of a novel electrically conducting biocompatible polymer with degradable linkages for biomedical applications. *RS Symp Proc*. 2006;950:99-104.

doi: 10.1557/PROC-0950-D09-08

42. Subramanian A, Krishnan UM, Sethuraman S. Axially aligned electrically conducting biodegradable nanofibers for neural regeneration. *J Mater Sci Mater Med*. 2012;23:1797-1809.

doi: 10.1007/s10856-012-4654-y

43. Xu C, Guan S, Wang S, *et al*. Biodegradable and electroconductive poly(3,4-ethylenedioxythiophene)/ carboxymethyl chitosan hydrogels for neural tissue engineering. *Mater Sci Eng C Mater Biol Appl*. 2018;84:32-43.

doi: 10.1016/j.msec.2017.11.032

44. Huang L, Hu J, Lang L, *et al*. Synthesis and characterization of electroactive and biodegradable ABA block copolymer of polylactide and aniline pentamer. *Biomaterials*. 2007;28(9):1741-1751.

doi: 10.1016/j.biomaterials.2006.12.007

45. Baheiraei N, Yeganeh H, Ai J, Gharibi R, Azami M, Faghihi F. Synthesis, characterization and antioxidant activity of a novel electroactive and biodegradable polyurethane for cardiac tissue engineering application. *Mater Sci Eng C Mater Biol Appl*. 2014;44:24-37.

doi: 10.1016/j.msec.2014.07.061

46. Xie M, Wang L, Ge J, Guo B, Ma PX. Strong electroactive biodegradable shape memory polymer networks based on star-shaped polylactide and aniline trimer for bone tissue engineering. *ACS Appl Mater Interfaces*. 2015;7:6772-6781.

doi: 10.1021/acsami.5b00191

47. Boutry CM, Sun W, Strunz T, Chandrahalim H, Hierold C. Development and Characterization of Biodegradable Conductive Polymers for the Next Generation of RF Bio-Resonators. In: *Proceedings of the IEEE International Frequency Control Symposium*; 2010. p. 1-4.

doi: 10.1109/FREQ.2010.5556332

48. Lu Y, Li T, Zhao X, *et al*. Electrodeposited polypyrrole/ carbon nanotubes composite films electrodes for neural interfaces. *Biomaterials*. 2010;31:5169-5181.

doi: 10.1016/j.biomaterials.2010.03.022

49. Wan P, Yuan C, Tan L, Li Q, Yang K. Fabrication and evaluation of bioresorbable PLLA/magnesium and PLLA/magnesium fluoride hybrid composites for orthopedic implants. *Compos Sci Technol*. 2014;98:36-43.

doi: 10.1016/j.compscitech.2014.04.011

50. Ghaziof S, Mehdikhani-Nahrkhalaji M. Preparation, characterization, mechanical properties and electrical conductivity assessment of novel polycaprolactone/multi-wall carbon nanotubes nanocomposites for myocardial tissue engineering. *Acta Phys Pol A*. 2017;131:428-431.

doi: 10.12693/APhysPolA.131.428

51. Wang H, Chiang P, Tzeng J, *et al*. *In vitro* biocompatibility, radiopacity, and physical property tests of nano-Fe3O4 incorporated poly-l-lactide bone screws. *Polymers*. 2017;9:191.

doi: 10.3390/polym9060191

52. Jiang C, Wang K, Liu Y, Zhang C, Wang B. Using wet electrospun PCL/gelatin/CNT yarns to fabricate textile-based scaffolds for vascular tissue engineering. *ACS Biomater Sci Eng*. 2021;7:2627-2637.

doi: 10.1021/acsbiomaterials.1c00097

53. Sumitha MS, Shalumon KT, Sreeja VN, Jayakumar R, Nair SV, Menon D. Biocompatible and antibacterial nanofibrous poly(∈-caprolactone)-nanosilver composite scaffolds for tissue engineering applications. *J Macromol Sci A*. 2012;49:131-138.

doi: 10.1080/10601325.2012.642208

54. Rivers TJ, Hudson TW, Schmidt CE. Synthesis of a novel biodegradable electrically conducting polymer for biomedical applications. *Adv Funct Mater*. 2002;12(1):33-37.

doi: 10.1002/1616-3028(20020101)12:1<33:AID-ADFM33>3.0.CO;2-E

55. Da Silva ACB, Semeano ATS, Dourado AHB, Ulrich H, Cordoba De Torresi SI. Novel conducting and biodegradable copolymers with noncytotoxic properties toward embryonic stem cells. *ACS Omega*. 2018;3:5593-5604.

doi: 10.1021/acsomega.8b00510

56. Song F, Jie W, Zhang T, *et al*. Room-temperature fabrication of a three-dimensional reduced-graphene oxide/ polypyrrole/hydroxyapatite composite scaffold for bone tissue engineering. *RSC Adv*. 2016;6:92804-92812.

doi: 10.1039/C6RA15267H

57. Yang S, Jang L, Kim S, *et al*. Polypyrrole/alginate hybrid hydrogels: Electrically conductive and soft biomaterials for human mesenchymal stem cell culture and potential neural tissue engineering applications. *Macromol Biosci*. 2016;16:1653-1661.

doi: 10.1002/mabi.201600148

58. Borah R, Upadhyay J, Acharjya K. Functionalized polyaniline: chitosan nanocomposites as a potential biomaterial. *Mater Today Proc*. 2020;32:334-343.

doi: 10.1016/j.matpr.2020.01.583

59. Jayaram AK, Pitsalidis C, Tan E, *et al*. 3D hybrid scaffolds based on PEDOT: PSS/MWCNT composites. *Front Chem*. 2019;7:363.

doi: 10.3389/fchem.2019.00363

60. Mohammad Alizadeh Z, Karbasi S, Arasteh S. Physical, mechanical and biological evaluation of poly (3-hydroxybutyrate)-chitosan/MWNTs as a novel electrospun scaffold for cartilage tissue engineering applications. *Polym Plast Technol Mater*. 2020;59:417-429.

doi: 10.1080/25740881.2019.1647244

61. Guo Y, Jia S, Qiao L, *et al*. A multifunctional polypyrrole/zinc oxide composite coating on biodegradable magnesium alloys for orthopedic implants. *Colloids Surf B Biointerfaces*. 2020;194:111186.

doi: 10.1016/j.colsurfb.2020.111186