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Biocompatible Electrode Materials for Bio-Integrated Energy Storage: Performance, Transport, Safety and Sustainability Trade-Offs

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Abstract

Increased demand for safe, sustainable, and bio-integrated energy storage devices has sparked greater interest in developing biocompatible electrode materials that can function in wearable, implantable, and environmentally friendly devices. Unlike traditional electrode materials, which have been optimized based on electrochemical properties, biocompatible electrodes must meet critical requirements in terms of electrical conductivity, charge storage, mechanical compliance, chemical stability, biological safety, and environmental sustainability. This article provides a comprehensive and critical review of four dominant classes of biocompatible electrode materials, which include carbon-based materials, conductive polymers, biopolymer-derived carbons, and biocompatible metal oxides, with special emphasis on their application in supercapacitors and other electrochemical energy storage devices.

We have developed a comprehensive and critical evaluation framework that includes electrochemical properties (specific capacitance, energy and power density, rate capability, and cycling stability), charge transport and kinetic properties (electronic conductivity, ion diffusion, charge transfer resistance, equivalent series resistance, and IR drop), structural and morphological properties (surface area, pore structure, mechanical flexibility, and mass loading), biocompatibility properties (cytotoxicity, inflammatory response, hemocompatibility, and implantability), chemical and environmental stability, and sustainability and manufacturability.

Carbon-based electrodes, including activated carbon, graphene, carbon nanotubes, and carbons derived from biomass, are recognized as the most reliable materials for high-power and long-cycle applications due to their excellent chemical inertness, low toxicity, high surface area, and excellent cycling durability. Conductive polymers such as PEDOT:PSS, polyaniline, and polypyrrole have demonstrated enhanced pseudocapacitance and mechanical softness, which are beneficial for flexible and bio-integrated applications, but the electrochemical stability and redox fatigue are the major challenges. Biopolymer-derived carbons have also demonstrated the possibility of developing sustainable materials using renewable sources such as cellulose, chitosan, and alginate, which have demonstrated excellent hierarchical porosity, electrochemical properties, and environmental compatibility. Biocompatible metal oxide materials such as MnO_2, TiO_2, Fe_3O_4, and ZnO have demonstrated excellent theoretical capacitance and energy density due to the faradaic charge storage mechanism, but the low intrinsic conductivity, ion transport, and dose-dependent toxicity are the major challenges.

Through a systematic comparison of these material classes, this review aims to shed light on some fundamental performance-biocompatibility-sustainability trade-offs, as well as derive design principles for optimizing electrode selection based on application-specific priorities. Finally, we outline some exciting opportunities in hybrid material architectures, green synthesis strategies, bio-resorbable electrodes, and advanced bio-integrated energy technologies, providing a forward-looking roadmap for the development of safe, sustainable, and high-performance biocompatible energy storage technologies.

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Keywords: Energy storage; Biocompatibility; Pseudocapacitance; Conductive polymers; Electrical Double Layer

1. Introduction

The increasing popularity of wearable electronics, implantable medical devices, and environmentally sustainable power technologies has created an urgent need for energy storage technologies that are not only high-performance but also biologically safe, mechanically compliant, and environmentally sustainable(1). The conventional electrode materials used in batteries and supercapacitors, which are often heavy metals, toxic solvents, or environmentally persistent chemistries, pose challenges for direct integration into biological systems as well as large-scale sustainable deployment(2). The convergence of energy storage technologies with human health, soft robotics, and environmentally sustainable technologies has created an exciting opportunity for the development of biocompatible electrode materials(3).

For the electrode materials to qualify as biocompatible, they must meet a multidimensional performance envelope that goes beyond the conventional parameters of electrochemical performance. Besides possessing competitive specific capacitance, energy density, power density, and cycling stability, the materials must also possess low cytotoxicity, low inflammatory response, chemical inertness in the body, low biofouling, and safe degradation profiles(4). Additionally, the materials must be scalable, sourced in a sustainable manner, and environmentally friendly, especially in the context of the emerging "green" energy storage technologies that conform to the "circular economy" concept(2). These additional requirements necessitate the development of a holistic materials selection approach that considers both the electrochemical performance of the materials, as well as their biological safety, mechanical, and sustainability profiles.

In the recent past, there has been an increased interest in electrode materials based on biologically compatible materials, especially in the development of bio-integrated supercapacitors, transient electronics, epidermal energy storage devices, and implantable microsystems(5). Among the many different materials approaches that have been explored, four classes of materials have shown the greatest promise: carbon-based materials, conductive polymers, biopolymer-derived carbons, and biocompatible metal oxide materials(6). These materials possess different advantages and disadvantages, especially in terms of charge storage, ion transport, mechanical compliance, durability, and biological compatibility, but the relative performance of these materials has been discussed in fragmented application-based contexts.

Carbon-based materials, including activated carbons, graphene, carbon nanotubes, and biomass-derived carbons, represent the most advanced and widely used materials in the development of biocompatible energy storage devices(7). These materials possess many advantages, including chemical inertness, large surface area, good electrical conductivity, and good cycling stability, especially in the development of high-power devices(8). However, the electric double-layer-based charge storage in these materials may limit their energy density, necessitating the development of hybrid materials with pseudocapacitive materials(9).

Conductive polymers, such as PEDOT:PSS, polyaniline, and polypyrrole, offer a promising route forward, which combines electronic conductivity with pseudocapacitive charge storage and softness(9). These materials are of particular interest for flexible, stretchable, and bio-integrated devices, such as neural interfaces and soft bio-electronics(10). Although they offer the highest theoretical capacitance values and can be processed easily, degradation, volumetric changes, and long-term redox stability represent the main challenges hindering the widespread application of conductive polymers(11).

Biopolymer-derived carbons, which can be produced from a variety of renewable sources, such as cellulose, chitosan, alginate, silk fibroin, and lignin, represent a new and rapidly expanding class of sustainable and environmentally friendly electrode materials(12). These materials can exhibit hierarchical porosity, competitive electrochemical performance, and favorable mechanical properties, in addition to the important advantages of renewable feedstock, low toxicity, and low environmental impact(13). In this regard, the integration of biopolymer-derived carbons in the field of energy storage can be viewed as a highly promising approach in the context of green chemistry and the design of bio-resorbable or transient electronics.

Biocompatible metal oxide materials, such as MnO_2, TiO_2, Fe_3O_4, and ZnO, offer the potential for accessing the highest theoretical capacitance and energy density values through the faradaic charge storage mechanism(14). A number of the materials in this class have already shown clear biomedical relevance in terms of implantology, imaging, and drug delivery. However, low intrinsic conductivity, limitations in terms of ionic conductivity, structural changes during

cycling, and potential dose-dependent toxicity represent the main challenges that need to be addressed in the design of these materials for bio-integrated devices.

Although significant advancements have been achieved for all of these material families, a comprehensive comparative tool for evaluating biocompatible electrodes has not been established. Most of the literature reports on various aspects of material performance or focuses on a specific material system, which makes it hard to draw comprehensive design rules for bio-integrated energy storage devices. A systematic review that relates electrochemical properties to charge carrier kinetics, structural features, biocompatibility, chemical stability, and sustainability is a necessity.

In this review article, we present a comprehensive and critical review of carbon-based materials, conductive polymers, biopolymer-derived carbons, and biocompatible metal oxides as potential platforms for energy storage applications. We propose a standard framework for the assessment of these materials in terms of their electrochemical performance, charge transport parameters, morphological and mechanical characteristics, biocompatibility, environmental sustainability, and manufacturability. By comparing and contrasting these classes of materials, we reveal the critical performance-biocompatibility-sustainability compromises and explore new hybrid and bio-inspired approaches to the development of safe, sustainable, and high-performance energy storage devices for bio-integrated and environmentally responsible technologies.

2. Defining Biocompatibility and Establishing an Evaluation Framework for Energy-Storage Electrodes

2.1. Biocompatibility in the Context of Energy-Storage Electrodes

In the context of biomedical engineering and bio-integrated technologies, biocompatibility is generally defined as the capability of a material to perform its intended function without causing adverse local or systemic effects in living tissues(15). When applied to energy storage electrodes, this definition extends from the lack of cytotoxicity to encompass a wide range of biological, chemical, mechanical, and environmental factors that influence the safety and reliability of the material in the context of bio-integrated applications(16).

Unlike traditional electrode materials that are engineered to meet stringent requirements in terms of electrical and electrochemical performance, biocompatible energy storage electrodes are required to operate in environments that involve potential interactions with human skin, bodily fluids, tissues, and other ecologically sensitive environments. In such contexts, the ideal biocompatible energy storage electrode should exhibit minimal toxicity, low inflammatory or immunogenic potential, high resistance to corrosion and ion leaching, chemical inertness in bio-environments, and stable performance during prolonged use(17).

In this review, the definition of a biocompatible electrode material will be considered as one that meets the following three criteria simultaneously: the capacity to provide reliable electrochemical energy storage performance, the capability to provide biological safety, and the compatibility with the principles of sustainability and environmental stewardship.

2.2. Scope of Materials Considered in This Review

The scope of the materials considered in this review covers the full gamut of four major classes of electrode materials that have already achieved or are likely to achieve biocompatible status. These include carbon-based materials, conductive polymers, biopolymer-derived carbons, and biocompatible metal oxides. These four material classes encompass the full range of charge storage mechanisms, material architectures, processing routes, and biocompatibility characteristics, thus allowing the review team to conduct the most comprehensive comparison.

The material classes considered here include the full gamut of electric double-layer capacitive, pseudocapacitive, and hybrid material architectures. These material classes were considered necessary for this review because the evaluation of their performance trade-offs is critical, especially with regard to their power, energy, mechanical flexibility, and sustainability characteristics. By restricting the scope of this review to these four material classes, the team focused on the most promising material classes that have achieved or are likely to achieve the best balance between material maturity, biocompatibility, and sustainability.

2.3. Charge-Storage Mechanisms Relevant to Biocompatible Electrode Materials

In order to evaluate the merits of the electrode materials considered in this review, the review team must first understand the basic mechanisms that govern the electrochemical behavior of the materials. Carbon-based materials, as well as biopolymer-derived carbons, store charge mainly via the electric double-layer capacitance mechanism, wherein ions are accumulated on the electrode-electrolyte interface(18) (19).

On the contrary, conductive polymers and metal oxides mainly exhibit pseudocapacitive storage modes, where fast and reversible redox reactions occur at or near the surface of the electrodes. This generally results in increased specific capacitance and energy density but may also lead to increased volumetric strains, kinetic limitations, and degradation(20).

Recently, many advanced types of electrodes have been developed to exhibit combined electric double-layer and pseudocapacitive storage modes by using combinations of carbon materials and polymers or metal oxides. These electrodes aim to exhibit balanced performance by increasing energy density without compromising power density, cycle life, and mechanical robustness.

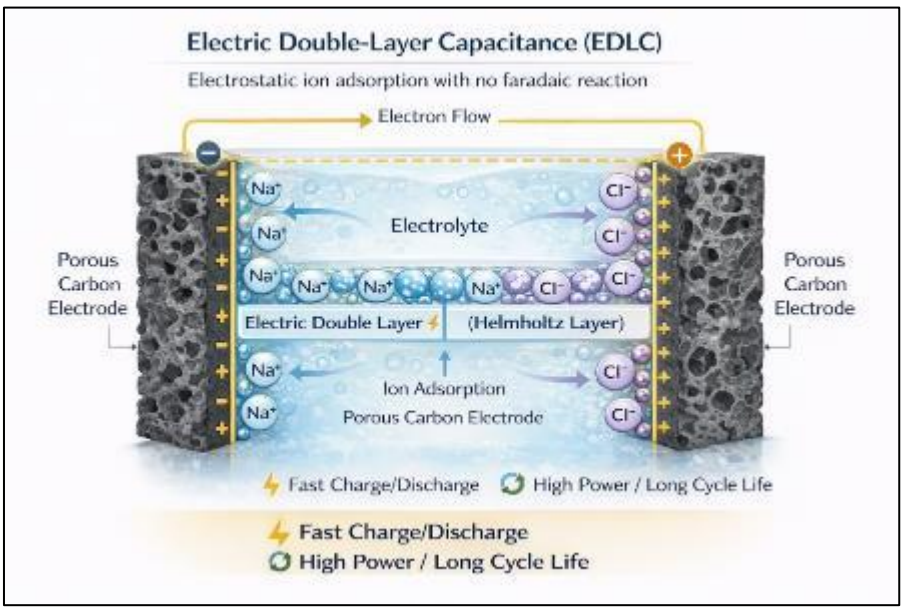

Figure 1 Schematic illustration of electric double-layer capacitance (EDLC) in porous carbon electrodes. Charge is stored through reversible electrostatic adsorption of electrolyte ions at the electrode–electrolyte interface, forming an electric double layer (Helmholtz layer) without faradaic redox reactions. The absence of bulk ion diffusion or chemical transformation enables rapid charge–discharge kinetics, high power capability, and excellent cycling stability, which underpin the widespread use of carbon-based materials in supercapacitor and bio-integrated energy-storage applications

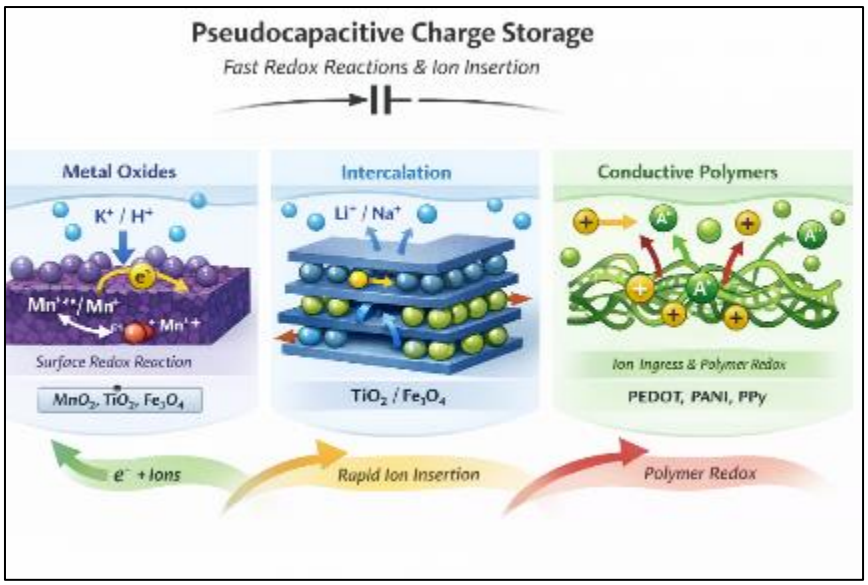

Figure 2 Schematic illustration of pseudocapacitive charge storage mechanisms relevant to conductive polymers and biocompatible metal oxide electrodes discussed in this review. In metal oxide electrodes (e.g., MnO_2, TiO_2, Fe_3O_4, ZnO), charge is stored through fast surface or near-surface redox reactions coupled with ion adsorption or shallow intercalation. In nanostructured oxide systems, rapid ion insertion into surface-accessible lattice sites enables capacitor-like faradaic behavior without slow bulk diffusion. In conductive polymers (e.g., PEDOT:PSS, polyaniline, polypyrrole), charge storage occurs through reversible redox reactions along polymer backbones accompanied by ion ingress into the polymer matrix. These pseudocapacitive mechanisms provide higher charge storage capacity than electric double-layer capacitance while introducing transport- and stability-related limitations that are discussed throughout this work

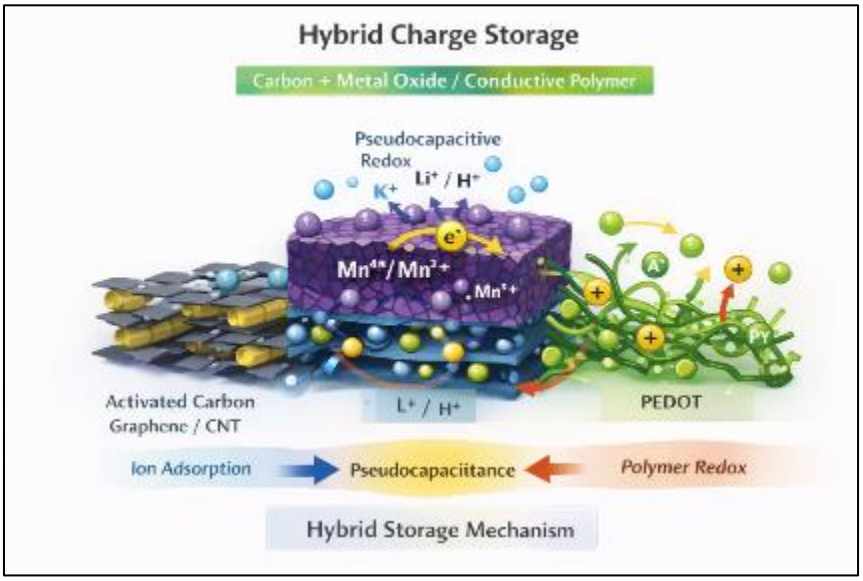

Figure 3 Schematic representation of hybrid charge-storage mechanisms in composite electrodes combining carbon materials with pseudocapacitive components (metal oxides and/or conductive polymers). Electric double-layer charge storage occurs on the carbon framework (activated carbon, graphene, CNTs) through electrostatic ion adsorption, providing high power capability and fast charge–discharge kinetics. Simultaneously, pseudocapacitive charge storage occurs via fast surface redox reactions and shallow ion insertion in metal oxides (e.g., MnO_2, TiO_2, Fe_3O_4, ZnO), as well as reversible redox processes along conductive polymer backbones (e.g., PEDOT:PSS, polyaniline, polypyrrole). The synergistic integration of these mechanisms enables hybrid electrodes to achieve enhanced energy density while preserving high power performance, cycling stability, and mechanical compliance, forming the dominant design strategy for high-performance biocompatible energy-storage systems

2.4. Multi-Dimensional Evaluation Framework

In order to compare the various types of materials systematically, this review has proposed a multi-dimensional evaluation framework that incorporates various types of electrochemical performance parameters, charge transport parameters, structural parameters, biological safety parameters, operational stability parameters, and sustainability parameters. This framework aims to extend the scope of evaluation beyond specific performance parameters to the overall functional regime required for biocompatible energy storage electrodes.

Electrochemical performance parameters have been evaluated on the basis of charge storage capacity, operational efficiency, and durability. These parameters include specific capacitance, areal capacitance, energy density, power density, rate capability, cycle life, and coulombic efficiency.

Charge transport parameters have been evaluated on the basis of the following parameters: electronic conductivity, equivalent series resistance, charge transfer resistance from impedance spectroscopy, diffusion coefficient of ions, charge-discharge IR drop from galvanostatic tests, and relaxation time constants.

In addition, structural, morphological, and mechanical properties are also taken into consideration, keeping in view their effect on the accessibility of ions, the integrity of the electrodes, and their compatibility in terms of form factors. Surface area, pore size distribution, mass loading, electrode thickness, flexibility, and resistance to structural fatigue after repeated cycles of charging and discharging are considered in order to assess the effect of the structure on the electrochemical and mechanical properties of the electrodes.

Biocompatibility and biological safety of the electrodes have been considered by taking into account the reported cytotoxicity, inflammatory markers, hemocompatibility, risks of ion leaching, sterilization tolerance, resistance to biofouling, and the potential of the electrodes to be safely integrated with living tissues. These properties help in assessing the suitability of the electrodes for direct or indirect use with living tissues.

Chemical, environmental, and operational stability of the electrodes, including resistance to corrosion, oxidative degradation, hydrolytic degradation, dissolution in aqueous or physiological electrolytes, thermal stability, and storage stability, have been taken into consideration. These properties are critical in assessing the suitability of the electrodes from the perspective of their safe and reliable use over time.

Lastly, the sustainability, scalability, and feasibility of the electrodes have been considered in the framework, keeping in view the practical constraints of their use in the real world. The suitability of the electrodes in terms of the content of renewable and bio-based feedstock, their eco-friendliness, toxicity of chemicals used in their processing, cost efficiency, scalability, recyclability, and safety have been considered.

2.5. Normalization and Cross-Comparison Strategy

Keeping in view the differences in the conditions of the experiments conducted by various researchers, the review strategy focuses on the normalized and context-aware interpretation of the results and the reported data on the performance of the electrodes. The comparisons have been made in terms of mass-normalized and area-normalized metrics, cycle-normalized stability, and electrolyte-normalized conditions.

Rather, the focus is on reproducible performance trends, mechanistic interpretations, and material-class-level information, allowing for the extraction of design principles that are generally applicable across different architectures, electrolytes, and conditions.

2.6. Role of the Framework in Guiding Material Selection

The evaluation framework developed in this section is the conceptual basis for the comparative analysis in the following sections of this review. By incorporating electrochemical, biological, mechanical, and sustainability-oriented parameters, it allows for objective material comparison while also emphasizing the interplay of energy density, power capability, durability, flexibility, safety, and sustainability.

Such a systematic approach is intended to achieve more than a comprehensive summary of the literature but also to guide the rational selection of materials and electrodes for future bio-integrated energy storage devices. By using a common set of performance parameters, it also allows for the identification of new opportunities and future research directions for the development of safe, sustainable, and efficient biocompatible electrodes.

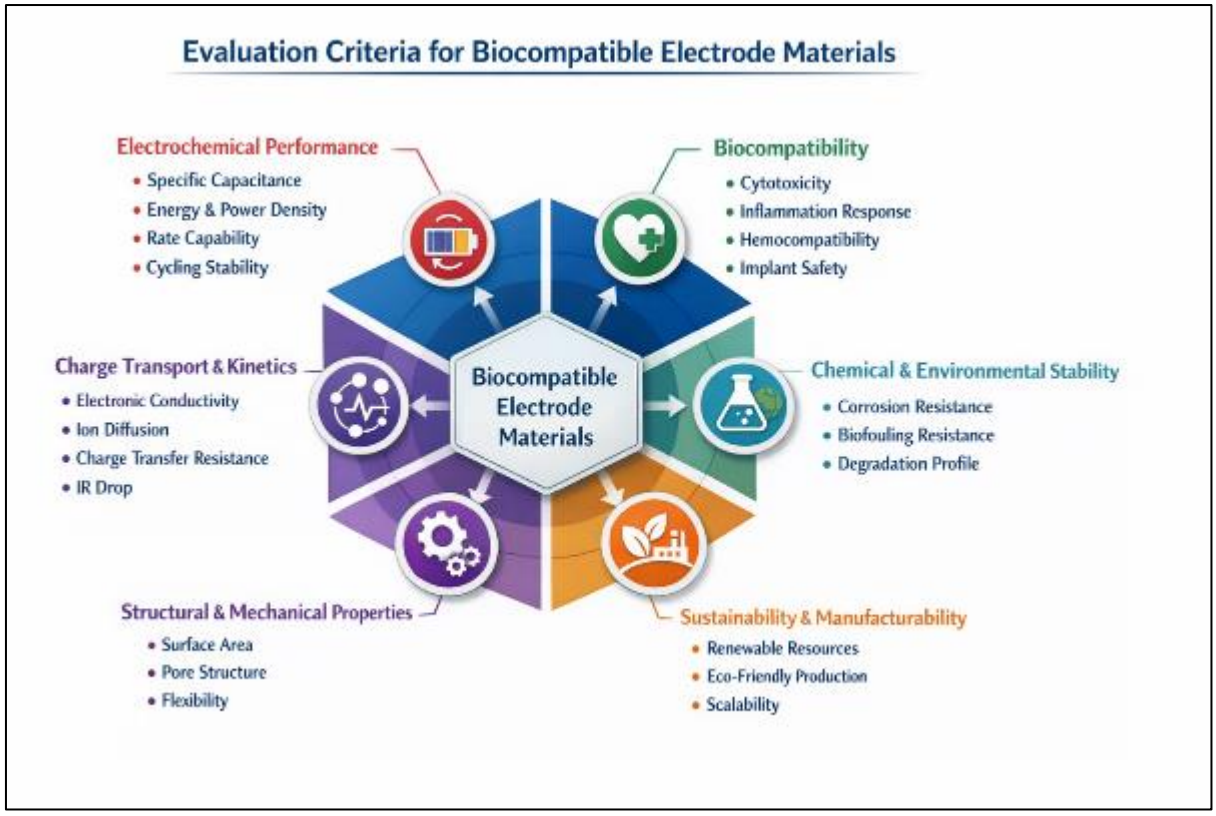

Figure 4 Summarizes the evaluation criteria of the bioelectrodes being discussed in this document. It provides a general overview of the various details to be discussed under each aspect

3. Carbon-Based Biocompatible Electrodes

Carbon-based materials represent the most well-established and commonly utilized family of electrode materials for biocompatible energy storage devices, owing to their chemical inertness, electrochemical properties, mechanical properties, and relatively low biological toxicity. Their long history of application in biomedical sensors, neural interfaces, water purification systems, and commercial-grade supercapacitors is a clear indicator of their reliability as safe and stable electrochemical systems(7) (18).

The primary electrochemical reaction in carbon electrodes is electric double-layer capacitance, where ions are electrostatically adsorbed on the electrode/electrolyte interface without redox reactions. The non-faradaic reaction mechanism allows for superior durability and cycling stability, with capacitance retention rates of over 90-95% even after 10,000 to 100,000 cycles. As such, carbon electrodes are most suitable for energy storage systems where long service lifetimes, mechanical reliability, and stable performance in aqueous environments are of primary importance(21).

The electrochemical characteristics of carbon materials are significantly affected by surface area, pore structure, electrical conductivity, and accessibility of the electrolyte(18). The most commonly used material for supercapacitors is commercial activated carbon, which is considered the reference material due to its high surface area, low cost, and ease of synthesis. The surface area of an activated carbon electrode is usually within the range of 800-2500 m^2/g, and its gravimetric capacitance is within the range of 80-300 F/g (22) (7) . The energy density of an activated carbon-based supercapacitor usually lies between 5 and 25 Wh/kg, whereas its power density usually exceeds 5-10 kW/kg, showing its good suitability for high-rate energy storage applications.

Graphene and CNTs are examples of advanced nanostructured carbon materials with superior electrical and mechanical properties(23). Graphene-based materials show superior electrochemical performance due to their two-dimensional charge transport and high theoretical surface area, resulting in capacitance values of 150-350 F/g, with low ESR and good rate capability(24) (25) (26). On the other hand, CNTs show superior power performance due to their continuous conducting network, which decreases charge-transfer resistance and increases the mobility of electrons. The

supercapacitor electrode made of CNTs shows a specific capacitance of 200-300 F/g, with capacitance retention of >95% after 5,000-20,000 cycles and a power density of >7 kW/kg(18).

Carbon-based materials also have good mechanical stability and flexibility, which make them suitable for the development of flexible, stretchable, textile-based, and wearable energy storage devices(18). For example, CNT fabrics, graphene films, and carbon aerogels have been successfully integrated into flexible supercapacitors, which have shown stable electrochemical performance after being subjected to various bending, twisting, and deformation tests(27). All of these properties make them suitable for bio-integrated energy storage devices.

One of the unique properties of carbon-based electrodes is their biocompatibility. Bulk carbon and activated carbon have been widely accepted as chemically inert and non-toxic. They have also shown low cytotoxicity and low inflammatory responses in biological systems. The fact that they have been widely used in various biomedical devices and adsorption-based drug delivery systems further underscores their biocompatibility(28). Although there have been some concerns regarding the biological responses of nanoscale carbon-based materials such as graphene and CNTs, surface modification and composite formation have been shown to eliminate any cytotoxicity while maintaining their electrochemical performance.

Despite the good performance of carbon-based electrodes, they have inherent limitations in terms of energy density due to their non-faradaic charge storage principle(7). This has led to the development of hybrid electrodes, where carbon-based frameworks have been integrated with other energy storage materials such as metal oxide and conducting polymers(21). This trend is now defining the new frontier of high-performance and bio-compatible carbon-based energy storage devices.

From a sustainability and manufacturing perspective, carbon electrodes have tremendous potential in terms of scalability, cost-effectiveness, and eco-friendliness(29). Activated carbon synthesis is already a mature technology, and new “green” synthesis routes for biomass-derived carbons are being explored to minimize environmental impact(30). Carbon-based electrodes can be fabricated by roll-to-roll coating, printing, electrospinning, and 3D printing, making them suitable for both conventional and novel energy storage devices(31).

In conclusion, carbon-based materials are the reference benchmark for biocompatible energy storage electrodes in terms of power performance, cycling stability, mechanical robustness, biological compatibility, and manufacturability. Although their energy density is relatively low in comparison to faradaic devices, their reliability, safety, and scalability make them a reference platform for bio-integrated energy storage devices. In the next section, we will discuss a new class of material, conductive polymer electrodes, which exhibit enhanced pseudocapacitance, mechanical softness, and unique opportunities for wearable and tissue-integrated devices.

3.1. Conductive Polymer Electrodes

Conductive polymers are a uniquely promising class of biocompatible electrodes, which are characterized by their ionic and electronic conductivity, redox activity, mechanical softness, and favorable interactions with biological media(4) (32). Unlike carbon-based electrodes, which utilize electric double-layer capacitance to store charge, conductive polymers exhibit pseudocapacitive faradaic charge storage, which allows for a significantly higher theoretical capacitance and energy density(21). Their intrinsic softness and flexibility make them ideal candidates for wearable, implantable, and tissue-integrated devices.

Among conductive polymers, poly(3,4-ethylenedioxythiophene)-polystyrene sulfonate (PEDOT:PSS), polyaniline (PANI), and polypyrrole (PPy) are the most studied materials for supercapacitor applications and bio-integrated devices(33). The reversible oxidation-reduction reactions of conductive polymers enable them to store charge not only at the electrode/electrolyte interface but also in the bulk of the polymers(34). Consequently, the specific capacitance of conductive polymer-based electrodes is found to be in the range of 300-1200 F g^{-1}, significantly higher than that of activated carbon-based electrodes, where the specific capacitance is found to be in the range of 80-300 F g^{-1} under similar conditions(35). Among conductive polymers, PEDOT:PSS is recognized as one of the most promising materials for supercapacitor applications due to its superior electrical conductivity, chemical stability, and neural biocompatibility. The specific capacitance of PEDOT-based supercapacitor electrodes is found to be in the range of 300-650 F g^{-1}, with energy density ranging from 10-35 Wh kg^{-1}, and power density >5 kW kg^{-1}. The cycling stability of PEDOT:PSS-based supercapacitors is found to be up to 80-95% capacitance retention after 5,000-20,000 cycles(36). Polyaniline-based supercapacitors have been reported to have some of the highest pseudocapacitance performance, with gravimetric capacitance >600-1200 F g^{-1}, areal capacitance >2-5 F cm^{-2}, and energy density up to 30-45 Wh kg^{-1},

similar to lower-end lithium-ion batteries, with power density >2-6 kW kg^{-1}(37). However, the degradation of PANI-based supercapacitors occurs due to the swelling of the polymers during redox reactions, resulting in capacitance retention of only 60-85% after 3,000-10,000 cycles(33).

Polypyrrole has similar pseudocapacitive characteristics, which yield a specific capacitance ranging from 350 to 900 F g^{-1}, depending on the method of synthesis and the electrolyte used. PPy electrodes have achieved an energy density of 15–30 Wh kg^{-1} and a stable rate performance up to moderate current densities(33)(38). However, the material is mechanically brittle and prone to structural failure during prolonged cycling. Capacitance retention for PPy systems ranges from 70 to 90% after 5,000 cycles, indicating the need for improving stability.

The charge transport in conductive polymer electrodes occurs by electron transport along the polymer backbone and ion diffusion through the hydrated polymer network. Although doped polymers, like PEDOT:PSS, can achieve conductivity values > 500–1,000 S cm^{-1}, the conductivity of PANI and PPy systems is relatively lower than their carbon counterparts(4). Electrochemical impedance spectroscopy also shows relatively higher values of Nyquist semicircle diameters and equivalent series resistance, indicating slower interfacial charge transfer kinetics and ion diffusion. These systems also show relatively higher IR drop and lower power density during high CDRs(39).

Mechanical compliance is one of the most important advantages of conductive polymers. Their low elastic modulus, flexibility, and ability to be used with hydrogel and elastomeric substrates make them suitable for soft tissues and deformable electronics(40). PEDOT:PSS films and polymer composites have been successfully integrated into flexible, stretchable, and textile-based supercapacitors, which retain their electrochemical characteristics even during repeated bending, stretching, and twisting deformations(41) (42). These characteristics make them particularly suitable for epidermal energy storage, implantable bioelectronic devices, and soft robotics.

Biocompatibility studies have consistently demonstrated the low cytotoxicity, excellent tissue compatibility, and low inflammatory response of PEDOT:PSS, making it a promising candidate for neural probes, cochlear implants, and cardiac devices. Polyaniline and polypyrrole have also demonstrated good cytocompatibility, but the presence of monomer residues, acidic dopants, and degradation products may cause dose-dependent cytotoxicity(43) (44) . Surface passivation, the use of neutral dopants, and polymer-biopolymer composites have also been found to significantly enhance the biological safety of the materials without compromising their electrochemical properties(45).

Although conductive polymer electrodes have demonstrated excellent electrochemical properties, they are also plagued by the problem of electrochemical degradation, volume changes, and fatigue, which limit their long-term cycling stability(33). During electrochemical reactions, the insertion and removal of ions cause polymer chain rearrangement, resulting in cracks and delamination, which reduces the electrode's surface area and connectivity(46). These degradation processes are believed to be one of the major bottlenecks that have prevented conductive polymers from achieving the cycling lifetimes observed with carbon electrodes.

To overcome these limitations, the hybrid structure of conductive polymers and carbon nanostructures or carbon scaffolds has been extensively explored. These polymer-carbon composites have demonstrated enhanced mechanical properties, lower resistance, and improved cycling stability, while maintaining the high pseudocapacitance values of the polymers. For instance, the capacitance values of the graphene-PANI composites have been reported to be around 500-850 F g^{-1}, with capacitance retention of more than 90% even after 10,000 cycles, which is significantly higher than the values reported for pure polymers(47).

In terms of sustainability and manufacturability, conductive polymers have both positive and negative aspects. Solution processability of CPs allows for low-temperature fabrication, printing, coating, and roll-to-roll processing, which is highly desirable for large-scale production. Yet, many synthesis methods require toxic oxidizers, organic solvents, and petroleum-based reagents, which have negative consequences for the environment. New “green chemistry” approaches and hybrid bio-polymer/polymer systems are being developed to minimize environmental impact and increase sustainability(48).

In summary, conductive polymer electrodes play a pivotal role in the field of biocompatible energy storage materials, providing high pseudocapacitive energy density, mechanical softness, and bio-integrated application potential. Though their cyclic and long-term stability is still lower than that of carbon-based electrodes, continuous improvements in composite materials, polymer chemistry, and mechanical reinforcement will ensure that this gap continues to decrease. In the next subsection, biopolymer-derived carbon electrodes will be discussed as a promising class of renewable and

bio-compatible energy storage materials that have shown great promise in terms of their environmental and biological compatibility, as well as their electrochemical properties.

3.2. Biopolymer-Derived Carbon Electrodes

Biopolymer-derived carbon electrodes have gained significant attention in the field of bio-compatible and renewable energy storage materials, providing a promising platform that unifies renewable energy sources, environmental sustainability, and competitive electrochemical properties(49). Unlike traditional fossil-derived carbon materials, biopolymer-derived carbon electrodes have been shown to be derived from renewable and bio-abundant sources, such as cellulose, lignin, chitosan, alginate, gelatin, silk fibroin, and agricultural wastes. These materials have been shown to have great promise in terms of their bio-compatibility, environmental sustainability, and electrochemical properties(50).

Biopolymer-derived carbon electrodes have been shown to have electric double-layer capacitance properties, similar to traditional activated carbon, and have shown promising results in terms of high charge storage capacity and cyclic stability(51). Moreover, due to their biological origin, they have been shown to have an intrinsic hierarchical porosity that allows for efficient ion transport, thereby providing high charge storage capacity and cyclic stability(52). As a result, many of these bio-derived carbon electrodes have been shown to have high surface areas, ranging from 800 to 2000 m^2/g.

In terms of quantitative performance, biopolymer-derived carbon electrodes generally exhibit gravimetric capacitance values ranging from 120 to 450 F g^{-1} in aqueous electrolytes. This places them firmly within or even beyond the performance window of conventional activated carbons. For example, porous carbon electrodes derived from cellulose have been found to exhibit capacitance values of 280-420 F g^{-1} along with energy density ranging from 8 to 22 Wh kg^{-1} and power density exceeding 5-9 kW kg^{-1}(53). Similarly, activated carbons derived from lignin have been found to exhibit specific capacitance values of 150-300 F g^{-1} along with capacitance retention of 85-95% even after 10,000 to 20,000 charge-discharge cycles(51).

Chitosan-derived carbon electrodes have also been found to exhibit capacitance values of 200-350 F g^{-1}. Nitrogen surface groups were found to play a significant role in improving wettability and ion accessibility(54). Similarly, activated carbons derived from alginate have been found to exhibit capacitance values exceeding 300 F g^{-1} along with energy density of 20-25 Wh kg^{-1}. This demonstrates the potential of renewable carbon materials to compete favorably with fossil-derived carbon materials.

The charge transport characteristics of biopolymer-derived carbon electrodes have been found to be significantly dependent on the pore size distribution, heteroatom doping, and graphitization degree(55). Electrochemical impedance spectroscopy of biopolymer-derived carbon electrodes has been found to exhibit low charge transfer resistance along with minimal IR drop, similar to conventional activated carbon electrodes. Well-engineered mesoporous carbon electrodes exhibit high rate capability retention exceeding 70-90%(7). Furthermore, the relaxation time constants have been found to be well below 1 s, thus demonstrating the strong potential of biopolymer-derived carbon electrodes for high-power supercapacitor applications.

In these materials, the role of surface chemistry is particularly significant, especially when the biopolymer precursor contains oxygen, nitrogen, and/or sulfur-containing functional groups, which are known to increase the wettability of the electrolyte and, in some instances, contribute to a certain level of pseudocapacitance(18). For example, nitrogen-doped biomass carbons have shown capacitance increases of 20 to 40 percent over their undoped counterparts, ascribed to improved kinetics of charge transfer and surface redox reactions(56). However, in some instances, over-doping with heteroatoms can also negatively impact the electrical conductivity of the material.

From a mechanical perspective, biopolymer-derived carbon electrodes have shown promising properties in terms of structural robustness and stability, as a result of naturally templated fiber networks and pore architectures(57). Carbon aerogels derived from cellulose and lignin precursors have shown promising properties in terms of lightweight architectures, compressive robustness, and flexibility, thereby paving the path for wearable, textile-based, and deformable energy storage devices(58). The electrochemical properties of these materials have shown promise even under repeated bending or compressive strains, thereby emphasizing their viability for bio-integrated electronics.

One of the most significant advantages of using biopolymer-derived carbon electrodes is their biocompatibility. As a result of using naturally benign precursors, these materials have shown promise in terms of low cytotoxicity, low

inflammatory responses, and environmentally safe properties(59). Studies based on cellulose-derived carbons, as well as chitosan-derived carbons, have shown promising properties in terms of high cell viability and low adverse biological responses, thereby paving the path for bio-integrated energy storage devices(60). In addition, the absence of heavy metals and toxic synthetic precursors is an added advantage.

The sustainability of biopolymer-derived carbon electrodes is a significant advantage, as a result of using renewable precursors, valorization of wastes, and using low-cost agricultural byproducts. The production of these materials is more environmentally friendly, as they show significant promise in terms of lower carbon footprint as compared to conventional petroleum-derived carbons(61). In addition, life-cycle analyses have shown promise in terms of lower greenhouse emissions and lower environmental toxicity, as a result of using environmentally safe activation strategies and low-temperature processing. The biodegradability of these materials is an added advantage, as they show significant promise as environmentally safe energy storage devices(62).

However, these biopolymer-derived carbon materials also possess some performance limitations with regard to their electrical conductivity, structural uniformity, and scalability. For instance, biocarbon materials derived from biomass precursors are known to possess lower intrinsic electrical conductivity compared to some of the most graphitized synthetic carbon materials(18). This results in lower power density, which can be overcome using hybrid composite materials(19).

To overcome the aforementioned performance limitations of biopolymer-derived carbon materials, researchers have employed a variety of hybrid materials comprising these materials and other additives such as graphene, carbon nanotubes, and polymers. These materials have been reported to possess capacitance values of >400-600 F/g. These results suggest the potential of biopolymer-derived carbon materials for achieving performance parity with the most advanced synthetic materials. These results are significant with regard to the increasing viability of sustainable, high-performance, and biocompatible carbon materials(63).

In conclusion, biopolymer-derived carbon materials possess significant strategic importance with regard to their ability to bridge the gap between electrochemical performance, biocompatibility, and sustainability. Although these materials do not possess energy density and conductivity superior to the most optimized synthetic materials and polymers, they are critical with regard to their renewable nature, biocompatibility, and competitive performance characteristics. In the next section, biocompatible metal oxide materials are discussed as an alternative with regard to their ability to possess significantly higher energy density and faradaic charge storage mechanisms.

3.3. Biocompatible Metal Oxide Electrodes

Biocompatible metal oxide-based materials have a unique place in bio-integrated energy storage systems as they can provide significantly higher charge storage values compared to electric double-layer-based systems via rapid and reversible faradaic reactions, and also leverage the familiarity of metal-based chemistry in bio-compatible environments(64). Among the metal oxide-based materials, manganese dioxide (MnO_2), titanium dioxide (TiO_2), iron oxide (Fe_3O_4), and zinc oxide (ZnO) are among the most researched oxide-based materials for aqueous-based supercapacitors and hybrid energy storage devices, mainly due to their relative availability and, under appropriate conditions, bio-compatibility. Nevertheless, metal oxide-based energy storage faces a number of challenges, which become important when the bio-compatible aspect is considered. These challenges include lower electronic conductivity compared to carbon-based materials, ion transport limitations, dissolution of the material in aqueous environments, and possible dose- and exposure pathway-dependent toxicity of metal oxide nanoparticles(65).

One of the main advantages of transition metal oxide-based materials is their ability to exhibit pseudocapacitance, where charge is stored via rapid and reversible surface or near-surface reactions(64). This can provide higher values of capacitance compared to electric double-layer-based materials, although this is usually limited by possible resistive and diffusion-related losses within the oxide structure. In this regard, highly performing oxide-based electrodes are usually nanostructured (nanosheets, nanorods, nanotubes, porous films) and/or contain conductive scaffolding (carbon black, graphene, CNTs, and conductive polymers)(66).

MnO2 is considered to be one of the key 'biocompatible-leaning' pseudocapacitive oxides because it has been characterized as relatively low-toxicity compared to other redox oxides, yet it has strong charge storage activity in aqueous systems. Reviews on MnO2 capacitance show it to be in a wide range depending on the phase, morphology, and architecture, but many MnO2-based electrodes in aqueous systems show specific capacitance in the range of ~100-300 Fg^{-1} under normal testing conditions, though higher capacitance has been reported in some nanostructured and

composite materials(67). For example, in a recent open-access publication on MnO2 composites, the specific capacitance of an MnO2-containing nanocomposite has been found to be ~318 Fg^{-1} at low scan rate, demonstrating the potential of the composite to show superior performance. More specifically, the phase dependence of MnO2 has been highlighted in the literature, with δ-MnO2 commonly found to show specific capacitance in the range of ~80-110 Fg^{-1}, which demonstrates the dependence of the performance on the phase of the MnO2(68). The enhancement of MnO2 performance in the form of composites has been found to show strong cycling performance, with thousands of cycles reported in aqueous systems depending on the design and current density(69).

TiO_2, on the other hand, is often chosen not in consideration of its capacitance value but rather for its well-understood biomedical familiarity and chemical stability, as titanium dioxide and titanium-based materials in general are well discussed in the context of biomedical devices and application, even while the toxicity and exposure context of TiO_2 nanostructures is an area of active scrutiny(70). From an electrochemical perspective, TiO_2 is often challenged by low native electronic conductivity and relatively poor ionic conductivity, and as a result, most electrochemical discussions of supercapacitor devices based on titanium dioxide nanostructures involve nanotube arrays and composites with carbon. A recent report on titanium dioxide nanotube arrays demonstrates a high capacitance value of ~1382 mF cm^{-2} and superior cycling stability, defined as ~100% over the first 9000 cycles. However, in the context of electrochemistry in general, discussions of titanium dioxide nanostructures highlight relatively low capacity/capacitance and diffusivity challenges, even while emphasizing the value of nanostructure in enhancing accessible area for electrochemical devices.

Fe_3O_4 is also of interest as a "biomedical-adjacent" oxide, given the interest in iron oxides in biomedical applications, including as contrast agents and in biomedical-oriented nanoparticle-based systems, where the literature emphasizes that biocompatibility is highly dependent on size, coating, and route of exposure(71). In terms of energy storage, Fe_3O_4 also has conductivity and transport issues, although again, these can be mitigated by the inclusion of carbon and the formation of a composite material. A 2024 open-access article on oxide-carbon composites provides representative data for the capacitance of such materials (~95-96 F g^{-1} for some Fe_3O_4/C composites) and emphasizes the high coulombic efficiency and capacitance retention after cycling, reflecting the role of the carbon structure in facilitating the response of the oxide. However, in the high-performance regime, hybrid nanostructured materials that include Fe_3O_4 and other oxides and conductive components can achieve very high capacitance, as in the case of a 2024 open-access article on the electrochemical properties of a composite material, where capacitance of 946 F g^{-1} was reported for a NiO/Fe_3O_4 electrode and 1155 F g^{-1} was reported for a NiO/Fe_3O_4/rGO electrode, with cycling retention after 10,000 charge/discharge cycles(66). Although highly dependent on the specific material and electrochemical protocol, the common feature of all of the above results is that Fe_3O_4 works best in biocompatible energy storage as a component of a composite material where the conductive component reduces the effect of resistance and the oxide component provides the faradaic storage.

ZnO is particularly interesting with regard to biocompatible energy storage discussions due to its particular role at the intersection of "green synthesis" narratives and well-documented nanotoxicology concerns(72). On one hand, ZnO has been utilized within biocompatible polymers and proposed within environmentally benign electrode concepts such as green synthesis of ZnO nanoparticle-polymer systems for biocompatible supercapacitor electrodes. On the other hand, significant nanotoxicology research has demonstrated dose-dependent cytotoxic and genotoxic effects of ZnO nanoparticles, with dissolution and Zn^{2+} ion release being a significant mechanism; therefore, dose, concentration, and size are critical with regard to any "biocompatible ZnO electrode" discussion(73). In fact, ZnO supercapacitor performance can vary significantly across architectures and composites, and many of the most significant "ZnO-containing" supercapacitor architectures are, in fact, hybrids with ZnO playing a secondary role within a larger network of materials(21).

Within MnO_2, TiO_2, Fe_3O_4, and ZnO, transport and resistance are likely the most universal and fundamental level of discussion within a review. As a result of the inherently lower conductivity of these materials relative to carbon-based materials, impedance spectra are likely dominated by larger semicircle diameters and increased ESR. This is why these materials are most commonly utilized as a composite with carbon within the literature and why galvanostatic curves are likely dominated by increased IR drop at current reversal with regard to similar carbon-based materials within similar geometries and electrolytes. Within a review, these characteristics are likely most effectively considered as a combined function of electronic transport through the material, ion transport through pores and oxide material, and charge transfer at the oxide/electrolyte interface(74).

The biocompatibility of metal oxides should be viewed as conditional rather than absolute(75). TiO_2 and iron oxides have the advantage of considerable precedent in the field of biomedicine. However, it should be noted that biocompatibility can vary significantly at the nanoscale and following exposure routes(76). Thus, surface engineering,

purification, and encapsulation strategies should be emphasized. For ZnO, the current state of the toxicology literature should be discussed to distinguish between "biocompatible device" and "intrinsic nanoparticle biocompatibility." MnO_2 should be viewed as having a favorable position among the transition metal oxides employed for pseudocapacitance. However, it should be noted that the biocompatibility of MnO_2 also varies depending on the formulation and exposure scenario, particularly if the device is intended to be implanted(77).

Overall, biocompatible metal oxides add to the "design space" of bio-integrated energy storage devices by offering the potential for higher pseudocapacitive charge storage compared to carbon-based devices. However, in almost all cases, architecture-level solutions are required to mitigate transport-related problems and ensure biocompatibility. In the context of this review article, the "most robust" design rule is that oxides are never "biocompatible" in isolation but only as part of a hybrid system in which the carbon or copolymer matrix supplies conductivity and compliance, and the oxide supplies the pseudocapacitive functionality.

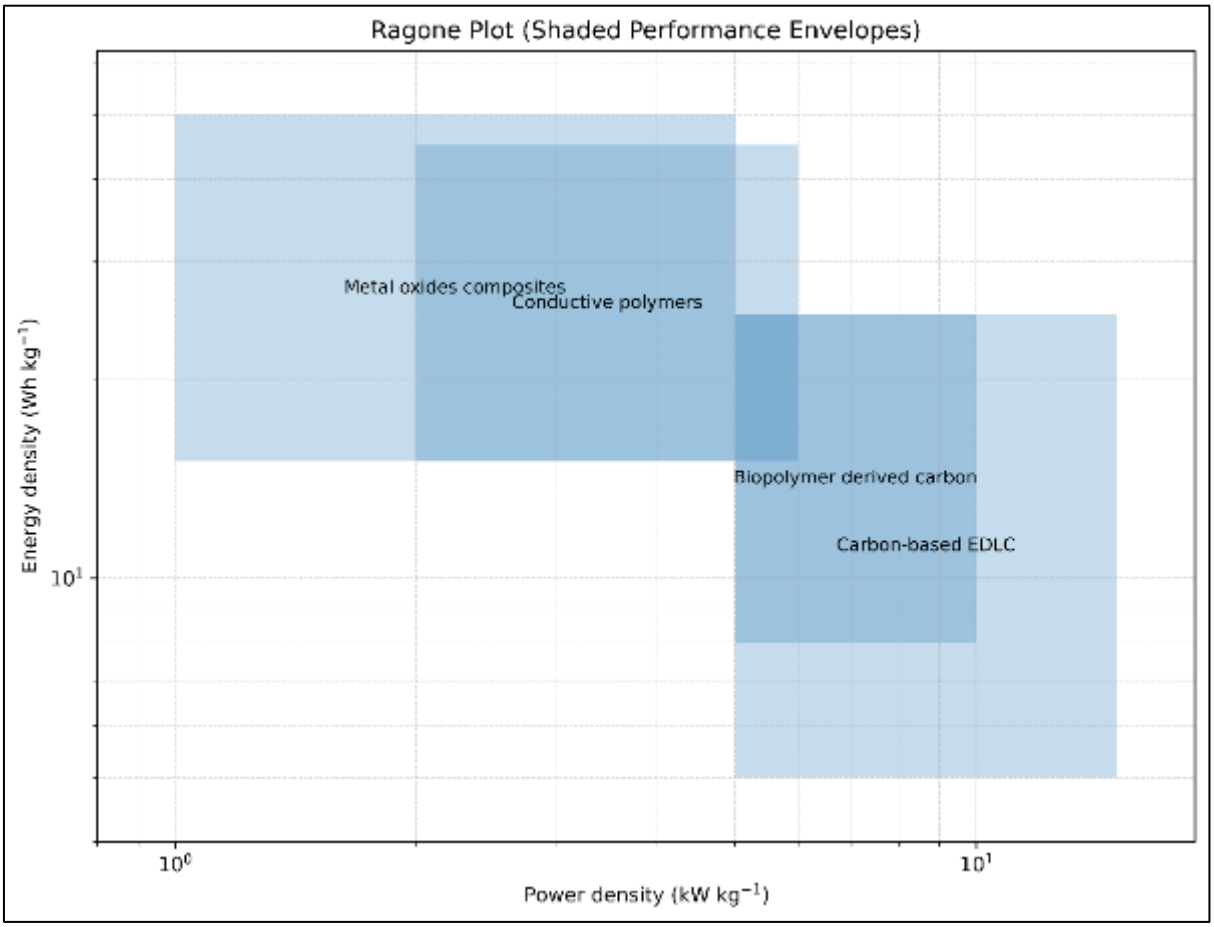

Figure 5 *Ragone plot illustrating the representative performance envelopes of major electrode material classes used in electrochemical energy-storage devices.* Shaded regions denote literature-derived ranges of gravimetric energy density and power density for carbon-based electric double-layer capacitors (EDLCs), biopolymer-derived carbons, conductive polymers, and metal-oxide-based composites. Carbon-based EDLCs and biopolymer-derived carbons exhibit superior power density and rate capability, reflecting fast non-faradaic charge storage and efficient ion transport. In contrast, conductive polymers and metal-oxide composites occupy higher energy-density regimes due to pseudocapacitive and faradaic contributions, albeit with comparatively reduced power performance. The overlap between shaded regions highlights the trade-off between energy and power density and underscores the potential of hybrid and composite architectures to bridge these performance domains

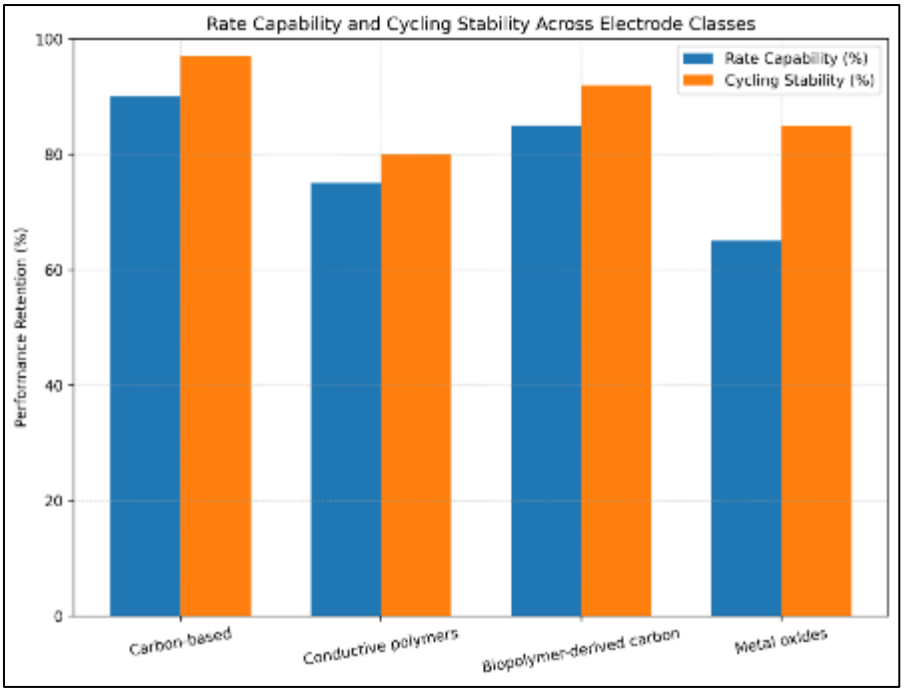

Figure 6 *Comparison of rate capability and cycling stability across representative electrode material classes.* Rate capability is expressed as capacitance or capacity retention at high current density relative to low-rate operation, while cycling stability represents performance retention after extended charge–discharge cycling. Carbon-based electrodes and biopolymer-derived carbons exhibit the highest overall stability and strong rate performance, reflecting non-faradaic or weakly faradaic charge storage mechanisms and robust structural integrity. Conductive polymers show moderate rate capability and cycling stability, limited primarily by volumetric changes and redox-induced degradation. Metal oxide electrodes display comparatively lower rate capability and cycling retention, consistent with slower ion diffusion kinetics and structural stress associated with faradaic processes

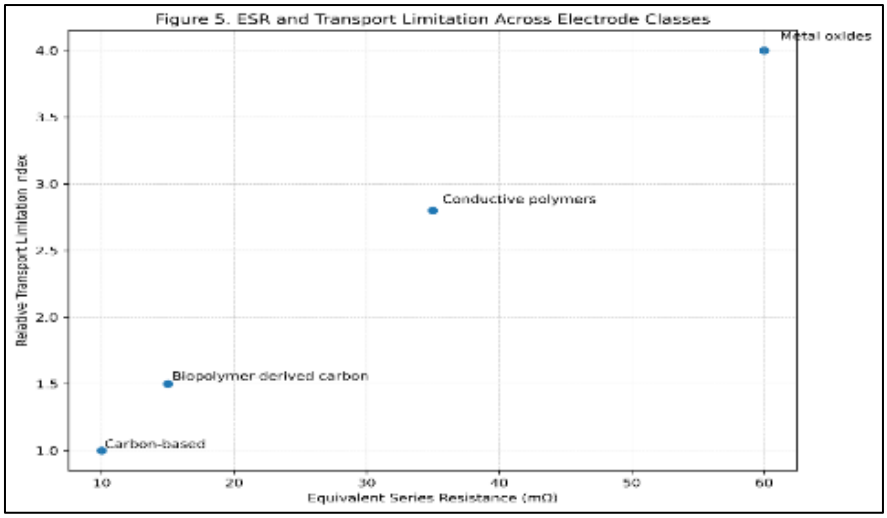

Figure 7 *Comparison of equivalent series resistance (ESR) and relative transport limitation across major electrode material classes.* The relative transport limitation index qualitatively represents combined ionic diffusion resistance, interfacial charge-transfer barriers, and electronic transport constraints inferred from electrochemical impedance trends. Carbon-based electrodes exhibit the lowest ESR and minimal transport limitations, consistent with highly conductive networks and fast non-faradaic charge storage. Biopolymer-derived carbons show slightly increased transport resistance due to hierarchical porosity and electrolyte accessibility effects, while conductive polymers display higher ESR associated with redox kinetics and polymer chain transport limitations. Metal-oxide electrodes exhibit the highest ESR and transport limitation, reflecting intrinsically lower electronic conductivity and diffusion-limited faradaic processes

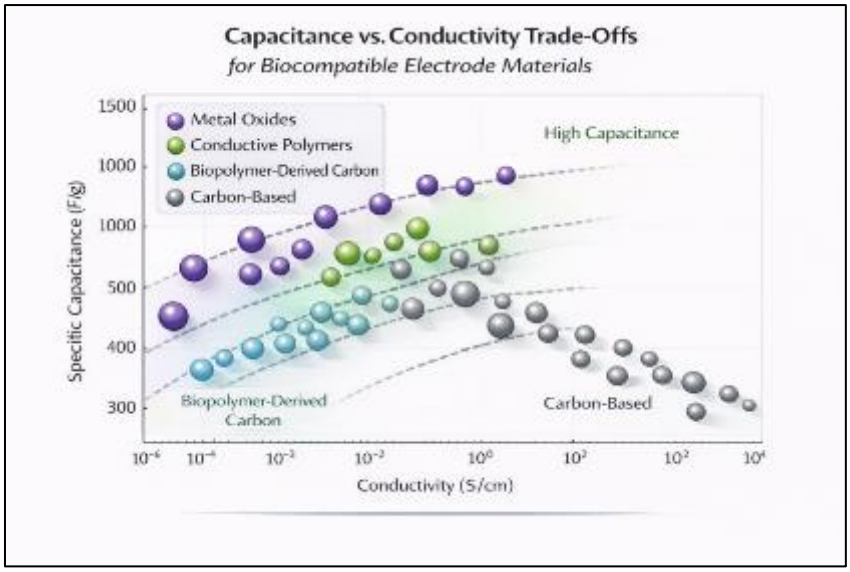

Figure 8 *Trade-off between specific capacitance and electrical conductivity for representative biocompatible electrode material classes.* The plot illustrates literature-derived performance trends for carbon-based materials, biopolymer-derived carbons, conductive polymers, and metal oxides, highlighting the inverse relationship between achievable capacitance and intrinsic electronic conductivity. Carbon-based electrodes exhibit the highest conductivities but comparatively lower capacitance due to purely electric double-layer charge storage. In contrast, metal oxides and conductive polymers achieve substantially higher capacitance through faradaic and pseudocapacitive mechanisms, albeit with reduced conductivity. Biopolymer-derived carbons occupy an intermediate regime, balancing moderate conductivity with enhanced capacitance arising from hierarchical porosity and surface functionalization. The dashed trend lines emphasize the fundamental materials design trade-offs relevant to biocompatible and bio-integrated energy storage systems

The table summarizes typical ranges of specific and areal capacitance, energy and power density, electrical conductivity, rate capability, cycling stability, and surface area for carbon-based materials, conductive polymers, biopolymer-derived carbons, and metal-oxide-based electrodes, based on representative literature reports. In addition, dominant transport and kinetic limitations, equivalent series resistance (ESR) ranges, ion-diffusion behavior, charge-transfer kinetics, and characteristic electrochemical impedance spectroscopy (EIS) signatures are compared to provide a unified framework for interpreting performance trade-offs across material classes. This comparative overview highlights the balance between conductivity, charge-storage mechanism, durability, and biocompatibility that governs material selection for bio-integrated and sustainable energy-storage systems.

Table 1 Comparative electrochemical performance, transport characteristics, and limiting factors of representative biocompatible electrode material classes

Electrode Class	Representative Materials	Charge Storage Mechanism	Specific Capacitance (F g⁻¹)	Areal Capacitance (F cm⁻²)	Energy Density (Wh kg⁻¹)	Power Density (kW kg⁻¹)	Electrical Conductivity (S cm⁻¹)	Rate Capability (% retention)	Cycling Stability (% retention)	Typical Surface Area	Key Strength
Carbon-Based	Activated carbon, graphene, CNTs, biomass carbon	EDLC	80–350	0.05–0.60	5–25	5–15	10^{-2}–10^{+4}	80–95% (90–99% [10k–100k	90–99% (10k–100k cycles)	800–3000	Ultra-fast charge, long lifetime
Conductive Polymers	PEDOT:PSS, PANI, PPy	Pseudo-capacitive	300–1200	0.50–5.00	15–45	2–6	10–1000	10–500	60–90% (5k–20k cycles)	Medium–High	Ultra-fast charge, long lifetime
Biopolymer Derived Carbon	Cellulose-C, lignin-C, chitosan-C,	EDLC + minor pseudo	120–450	0.08–0.70	8–25	5–10	10–500	10–500	70–90% (2k–20k cycles)	Medium	Renewable, green, safe
Metal Oxides (mostly composites)	MnO_2, TiO_2, Fe_3O_4, ZnO	Pseudo-capacitive	150–1100 (up to 1800 in nanos)	0.30–3.00	30–90% 2–5	50–90% (5k–200k cycles)	20–300	20–300	50–85% (5k–10k cycles)	Medium Mium	High energy potential

Class	Dominant Limiting Factor	Typical ESR (Ω)	IR Drop in GCD	Ion Diffusion Speed	Charge-Transfer Kinetics	EIS Nyquist Signature
Carbon	None (fast EDLC)	0.2–1.5	Very Low	Fast	Fast	Small semicircle
Conductive Polymers	Polymer swelling, ion-coupled redox	0.5–3.0	Moderate	Moderate	Moderate	Larger semicircle
	Conductivity variation	0.3–2.0	Low-Moderate	Fast	Fast	Similar to carbon
Metal Oxides	Low electronic conductivity	1.5–6.0	High	High	Slow-Moderate	Large semicircle, Warburg tail
Class	None (fast EDLC)	0.2–1.5	Very Low	Fast	Fast	Small semicircle
Conductive Polymers	Polymer swelling, ion-coupled redox	0.5–3.0	Moderate	Moderate	Moderate	Larger semicircle,
	Conductivity variation	0.3–2.0	Low-Moderate	Fast	Fast	Similar to carbon

Table 2 Qualitative biocompatibility, nanotoxicity, and sustainability assessment of major electrode material classes.

Class	**Cytotoxicity Risk**	**Inflammatory Response**	**Implant Suitability**	**Nanotoxicity Concern**	**Leaching / Dissolution Risk**	**Environmental Footprint**	**Renewable Feedstock**	**End-of-Life Safety**
Carbon	Low	Low	High	Low–Moderate (CNT/graphene)	Very Low	Medium	Medium–High	High
Conductive Polymers	Low–Moderate	Low	High	Low	Low	Medium	Low	Medium
Biopolymer Carbon	Very Low	Very Low	High	Very Low	Very Low	Low	High	Very High
Metal Oxides	Medium (dose-dependent)	Medium	Conditional	Medium–High	Medium	Medium	Low	Medium

The table provides a comparative overview of cytotoxicity risk, inflammatory response, implant suitability, nanotoxicity concerns, ion leaching or dissolution risk, environmental footprint, renewable feedstock availability, and end-of-life safety for carbon-based materials, conductive polymers, biopolymer-derived carbons, and metal oxides. Risk levels are assigned based on consensus trends reported in in vitro, in vivo, and environmental studies rather than absolute toxicity thresholds. The comparison highlights the favorable biocompatibility and sustainability profiles of biopolymer-derived carbons and conventional carbon materials, while emphasizing the dose-, size-, and dissolution-dependent safety considerations associated with metal oxides and certain nanostructured forms.

4. Conclusion

In the present review, a comprehensive and comparative analysis of the four major classes of biocompatible electrode materials has been provided, including carbon-based materials, conductive polymers, biopolymer-derived carbons, and biocompatible metal oxides, based on a set of guidelines and a unifying framework rather than isolated material properties and performance characteristics. By integrating the electrochemical characteristics, kinetic properties, structural aspects, biocompatibility, and sustainability of the materials, the review provides a unifying platform for the selection of the most promising materials for the construction of bio-integrated energy storage devices.

Among the materials considered, the carbon-based materials represent the most reliable class of materials for the construction of high-power and long-cycle-life electrodes and biostable electrodes, while the conductive polymers offer the benefits of high pseudocapacitive energy density and mechanical flexibility at the expense of long-term stability. The biopolymer-derived carbons offer the benefits of combining high electrochemical characteristics with sustainability and biocompatibility, while the metal oxides offer the benefits of high faradaic charge storage capacity at the expense of the need for architectural and composite material solutions to overcome the transport and dose-dependent toxicity issues.

The comparative analysis of the characteristics of the materials considered for the construction of bio-integrated energy storage devices highlights the fact that none of the materials considered possess all the characteristics required for the construction of the devices, and hybrid and composite materials and green synthesis strategies appear to hold the most promising solutions for the construction of the devices for the future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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