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Conductive Smart Scaffold for Electrochemical Sensing in Bone Tissue Engineering Applications: A Review

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Abstract

Tissue engineering technology using biomaterial-based scaffolds has been developed to support and regulate cellular activities, including cell adhesion, proliferation, migration, and the differentiation of electrically excitable cells through the incorporation of conductive materials. Conductive smart scaffolds have emerged as a promising platform for bone tissue engineering by integrating structural support with electrochemical sensing capabilities. Recent advances have enabled the development of conductive scaffolds integrated with electrochemical sensing systems for real-time, non-invasive monitoring of cellular behavior during bone regeneration. This review analyzes recent developments in electroactive conductive scaffolds and scaffold-based electrochemical sensing platforms for bone tissue engineering applications. A comprehensive literature review was conducted across major scientific databases to identify studies related to scaffold composition, conductive materials, electrochemical characterization methods, sensing strategies, and associated biological responses. The reviewed studies demonstrate that conductive polymers and carbon-based nanomaterials are widely used to enhance scaffold electroactivity and osteogenic performance. Electrochemical characterization techniques, including Cyclic Voltammetry (CV) and Electrochemical Impedance Spectroscopy (EIS), are commonly employed to evaluate scaffold conductivity, redox behavior, and electrochemical stability. Furthermore, conductive scaffold-based electrochemical sensing systems have been successfully applied to monitor cell viability, adhesion, proliferation, mineralization, and osteogenic differentiation in a label-free, non-destructive manner. The integration of conductive biomaterials with electrochemical sensing platforms enables precise monitoring of cellular activities through changes in electrical signals, impedance, and electrochemical responses. Overall, conductive smart scaffolds represent a promising multifunctional strategy for advancing bone tissue engineering by combining biocompatibility, electroactivity, regenerative capability, and real-time biosensing within a single scaffold system.

Keywords: Bone Scaffold, Carbon-Based Nanomaterials, Cell Function Monitoring, Cellular Behavior, Real-Time Biosensing.

INTRODUCTION

Tissue engineering aimed at replacing damaged organs is a complex process that involves the restoration of various biological functions (Amiryaghoubi et al., 2022). Biomaterial-based scaffolds have been developed to support cell adhesion and growth while maintaining biocompatibility with the host tissue (Zhang et al., 2023). An ideal scaffold for tissue engineering applications must have chemical and structural characteristics with good mechanical properties to support cell adhesion, proliferation, and differentiation, and may be fabricated from various natural and synthetic polymers (Jafari et al., 2017). However, in the fabrication of scaffolds for bone tissue engineering, the use only of natural polymers has limitations in mechanical stability and electrochemical properties, so the incorporation of additional materials with enhance functional properties is required (Shirehjini et al., 2022).

Conductive materials have been incorporated into scaffolds to enhance cellular activities, including cell adhesion, proliferation, migration, and differentiation of electrically excitable cells (Qu et al., 2019). Electrical stimulation has been shown to promote chondrocyte proliferation and accelerate bone repair *in vivo* (Miguel et al., 2022). However, most conventional methods for assessing cell function within scaffolds remain invasive and destructive, as they typically involve gene expression analysis or cytoplasmic protein labelling. Therefore, conductive smart scaffolds have been developed to both regulate cellular activity and enable real-time monitoring of cell adhesion and function (De Maria et al., 2014). In designing scaffolds suitable for cell culture and electrochemical monitoring, factors such as porous structure and biocompatibility of the material must be carefully considered. Furthermore, adequate electrochemical performance of the scaffold material is also necessary to enable fast and sensitive monitoring (Peng et al., 2023). Therefore, the use of conductive biomaterials together with polymer materials can be considered as potential candidates for bone scaffold development.

Various conductive materials can be incorporated as scaffold additives, including carbon nanoparticles (such as graphene and carbon nanotubes), metal nanoparticles and metal oxides (such as zinc oxide, gold, and silver), and conductive polymers (Miguel et al., 2022). Carbon-based nanostructures possess advantageous characteristics, providing electrical conductivity, mechanical reinforcement, and high surface area (Massoumi et al., 2021). Due to their favorable mechanical properties and low cytotoxicity toward osteocytes, carbon nanomaterials have been widely applied in bone tissue engineering (Ye et al., 2020). To date, conductive nanomaterials have also been utilized in the development of biosensors and are considered promising candidates for bone tissue engineering (Dixon & Gomillion, 2021).

In this study, we reviewed several studies related to conductive scaffolds for bone tissue engineering, particularly those designed for electrochemical sensing and electrical stimulation to support cell growth and development within the scaffold matrix. Considering the significant potential of conductive materials in enhancing electrical conductivity, mechanical properties, and biological performance, this review aims to evaluate current advancements in the design and application of conductive smart scaffolds. While numerous studies have reported the incorporation of conductive biomaterials to enhance scaffold performance, their role as integrated electrochemical sensing for real-time monitoring of cellular behaviour has not been explored. Specifically, the development of conductive smart scaffolds integrated with electrochemical sensing technologies may help improve strategies for bone regeneration by enabling non-invasive, real-time monitoring of cellular behaviour. Such advances are expected to support the development of advanced conductive scaffolds with improved functionality for bone tissue engineering, contributing to innovation in biomaterials and regenerative engineering.

METHOD

This review identifies recent developments related to conductive smart scaffolds as electrochemical sensing platforms in bone tissue engineering applications. A comprehensive literature search was conducted using online scientific databases such as Scopus and PubMed, supplemented by manual screening of relevant article bibliographies to ensure broader coverage of references. The article search strategy employed a combination of keywords align with the focus of the review, including "conductive smart bone scaffolds", "conductive electrochemical bone scaffold", "scaffold for electrochemical biosensor", "electrochemical characterization of bone scaffold", and "bone scaffold for cell monitoring". Articles published between 2015 and 2025 were collected and screened for relevance. The inclusion criteria were as follows: (1) the study was a scientific article written in English; (2) the study focused on the use of conductive biomaterials for scaffold function; and (3) the study reported information regarding the selected biomaterials, their electrochemical properties, and the application focused on bone tissue engineering. Articles that did not address the conductivity of scaffolds, did not include an electrochemical approach, or were not relevant to bone tissue engineering applications were excluded from the selection process. This study adopts an integrative literature review approach to synthesize findings from diverse studies in a multidisciplinary field involving biomaterials, electrochemistry, and tissue engineering.

The selection process was carried out in stages, starting with title screening, followed by evaluation of abstracts to assess their relevance to the review objectives. Articles that met the inclusion criteria were then subjected to review. A total of 12 articles were identified and as eligible and included in this review. The information collected was classified based on the type of material, electrochemical characterization method, and detection method according to the type of cells used for biosensing application in bone tissue engineering. This classification enables a structured comparison of different approaches reported in the literature. However, several limitations should be acknowledged. The findings of this review depend on the availability of published studies and may be influenced by publication bias. In addition, variations in experimental design, scaffold fabrication methods, and electrochemical measurement techniques across studies may limit direct comparability. Despite these limitations, this approach provides a comprehensive overview of the development of conductive smart scaffolds for electrochemical sensing applications in bone tissue engineering.

RESULTS AND DISCUSSION

Conductive Smart Scaffolds for Bone Tissue Engineering

Bone tissue engineering is a multidisciplinary science that aims to create implantable bone replacement structures capable of regenerating new bone without causing negative reactions (Awad et al., 2014; Tzavellas et al., 2020). The classical bone tissue engineering concept involves three main components, which are isolated cells, tissue growth factors, and scaffolds to create an osteogenic microenvironment that supports tissue regeneration (Wang & Yang, 2016). In the conventional tissue engineering paradigm, a combination of cells and growth factors in the form of active molecules is applied to a three-dimensional biomaterial scaffold to create osteogenic implants (Awad et al., 2014). The tissue engineering process begins with the identification and isolation of cells, which are then cultured under controlled conditions to allow proliferation and expansion. Subsequently, the cells are implanted onto or within the scaffold substrate and placed in a bioreactor to further promote growth. Finally, the scaffold is transplanted back into the host tissue (Rahmani et al., 2022). Within this structure, scaffolds play a critical role as supports and bioactive matrices that regulate cellular behavior, nutrient transport, and tissue integration (Jafari et al., 2017).

The ideal scaffold for bone tissue engineering involves the selection and characteristics of biomaterials that are important to consider (Lee et al., 2022). To be applicable to living organisms such as humans, all scaffold materials must have specific features, particularly being biocompatible and compliant with host biological fluids, tissues, and cells, without causing harmful local or systemic effects (Battafarano et al., 2021). Several natural or synthetic polymers have been used to develop biocompatible and biodegradable polymer constructs (Guo et al., 2021). Although natural polymers can be considered the first biodegradable biomaterials used clinically, various commercially available synthetic polymers also possess mechanical and physicochemical features comparable to biological tissues (Filippi et al., 2020). In addition, synthetic polymers have been investigated for various biomedical applications, mainly due to the possibility of precisely adjusting scaffold properties during fabrication (Fajarani et al., 2024; Nemati et al., 2019).

Recent developments in bone tissue engineering have shifted from passive scaffolds toward multifunctional smart scaffolds capable of actively interacting with cells and monitoring tissue regeneration processes in real time. Among these advanced bone scaffold, conductive scaffolds have emerged as promising platforms due to their ability to electrically stimulate cells and integrate electrochemical sensing functionalities into tissue engineering systems. As illustrated in Figure 1, conductive biomaterials can be incorporated into scaffold structures to support cellular activities while simultaneously enabling electrochemical characterization and monitoring during the bone regeneration process. The incorporation of conductive biomaterials is particularly relevant in bone regeneration because bone tissue itself exhibits intrinsic electrical conductivity, with conductivity values reported to be approximately 1.6–2.0 × 10^{-3} S/cm for cancellous bone and 5.8–6.3 × 10^{-4} S/cm for cortical bone (Marsudi et al., 2021). Therefore, one of the most common strategies for mimicking the native electrical microenvironment of bone tissue is the incorporation of conductive biomaterials into scaffold to improve scaffold conductivity and enhance electroactive cellular responses (Jadoun et al., 2021).

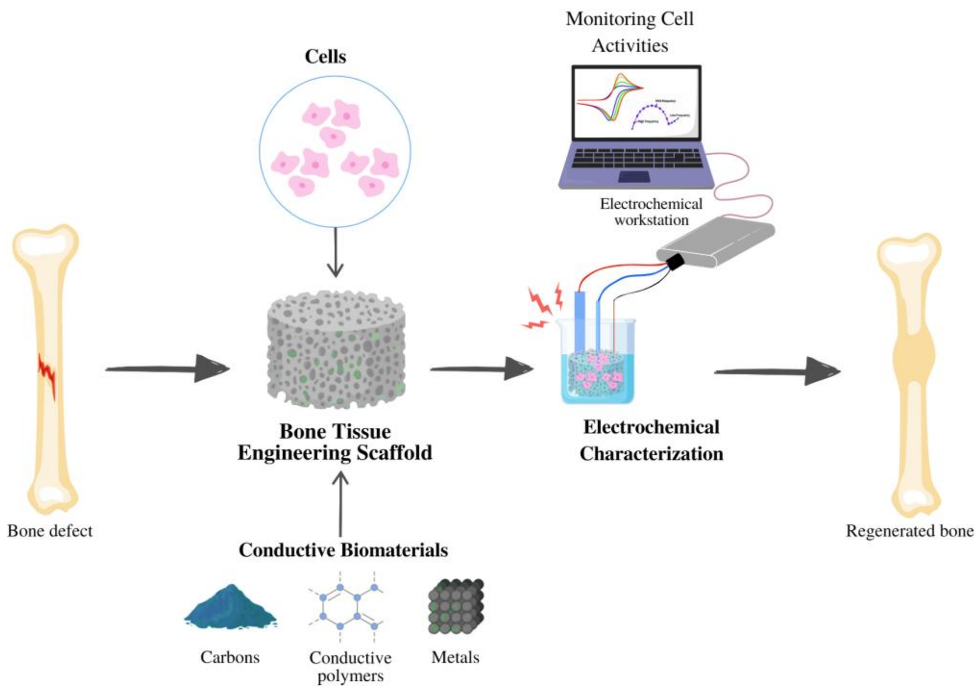

Figure 1. Schematic Illustration of Conductive Biomaterials Incorporated Into Bone Scaffolds and Integrated with an Electrochemical Sensing System

Conductive Materials in Bone Tissue Engineering

Conductive materials have been specifically added to polymer-based bone biomaterials as reinforcing elements and also as components capable of providing electrical signals through the application of electrical stimulation to promote osteoblast maturation and bone defect repair and regeneration (Arambula-Maldonado & Mequanint, 2022). Conductive bone scaffolds have the ability to transfer electrical and electromechanical signals directly to targeted cells, demonstrating the ability to enhance osteogenic proliferation and differentiation in vitro, as well as bone formation in vivo. The use of conductive materials can enhance several aspects of tissue regeneration, specifically enhancing cell-scaffold interactions such as adhesion and proliferation. Increased surface conductivity of scaffolds can lead to more efficient absorption and deposition of serum proteins, which aid in cell attachment and proliferation (Dixon & Gomillion, 2021).

Various conductive biomaterials have been investigated as functional additives in bone tissue engineering scaffolds, including carbon-based nanomaterials, metallic and metal oxide nanoparticles, and conductive polymers (Miguel et al., 2022). Carbon nanomaterials such as graphene and carbon nanotubes (CNTs) are particularly attractive because they provide high electrical conductivity, mechanical reinforcement, and high surface area (Massoumi et al., 2021)(Ye et al., 2020). Multiwalled carbon nanotube (MWCNT)-based scaffolds have demonstrated favorable characteristics for osteogenic cell adhesion, proliferation, and differentiation in vitro (Xu et al., 2019). Similarly, graphene-based materials and their derivatives, including graphene oxide (GO) and reduced graphene oxide (rGO), have been extensively investigated due to their excellent electrical conductivity, large surface area, and favorable biocompatibility, which collectively improve cell attachment and osteogenic differentiation (Bayan & Karak, 2020; Cheng et al., 2021; Sanati et al., 2022; Souza et al., 2022). In bone tissue engineering applications, the integration of rGO into scaffold matrices has been reported to enhance elastic modulus, mechanical strength, osteoconductivity, and osteoblast adhesion and proliferation in vitro (Raslan et al., 2020). Due to these advantageous physicochemical and electrochemical properties, CNTs and graphene nanosheets have also been extensively utilized in biosensor fabrication and are considered promising candidates for multifunctional scaffolds integrating regenerative and sensing capabilities (Dixon & Gomillion, 2021).

In addition to carbon-based materials, conductive polymers such as polyaniline (PANI) and polypyrrole (PPy) have also attracted significant interest for electroactive scaffold fabrication. These materials offer tunable electrochemical properties, facile synthesis, and good electrical conductivity, while carbon-based materials provide superior conductivity and mechanical reinforcement (T.-T. Li et al., 2023; Lou et al., 2023). Therefore, the combination of conductive polymers with biodegradable scaffold matrices has therefore become an important strategy for developing multifunctional electroactive scaffolds capable of supporting osteogenic regeneration.

Electrochemical Characterization of Conductive Bone Scaffolds

Electrochemical characterization represents a critical preliminary step in evaluating conductive scaffolds intended for bone tissue engineering and biosensing applications. Electrochemical analyses are essential to determine whether conductive scaffolds are capable of supporting electrical signaling, electroactive cellular interactions, and stable electron transfer behavior. Since electrical conductivity plays an intrinsic role in biological functions such as cell adhesion, migration, proliferation, differentiation, and DNA synthesis, especially in electrically responsive cells including osteoblasts, myoblasts, and fibroblasts, several researchers have proposed the development and fabrication of scaffolds incorporating electrically conductive biomaterials (Vandghanooni & Eskandani, 2019).

Amperometric-based electrochemical techniques are commonly employed to characterize the electrochemical behavior of scaffold materials and electrodes. Cyclic voltammetry (CV) is one of the most widely used techniques for evaluating the electrochemical response of three-electrode systems. This method is commonly applied to determine redox activity, electrochemical reversibility, electroactive material loading, and material stability (Yulianti et al., 2022). The appearance of oxidation and reduction peaks in CV curves generally indicates successful incorporation of electroactive components into scaffold matrices and reflects the ability of the scaffold to facilitate electron transfer processes (Fajarani et al., 2025).

Another important electrochemical technique widely applied in conductive scaffold studies is electrical impedance spectroscopy (EIS). EIS is an electrochemical technique used to measure bioimpedance over a range of frequencies, generating an impedance spectrum that reflects the electrical characteristics of the material or biological system (Ain et al., 2024). In scaffold-based systems, EIS is widely applied to evaluate conductivity, dielectric properties, ion transport behavior, and interfacial interactions between cells and biomaterials (Magar et al., 2021). Therefore, electrochemical characterization is important because it provides preliminary evidence regarding the ability of scaffolds to support electrical signaling and electroactive cellular interactions.

Electroactive Conductive Scaffold for Bone Tissue Engineering

Several studies have demonstrated the beneficial effects of conductive biomaterials on scaffold electroactivity and osteogenic performance. In our previous research, electrochemical characterization was performed to evaluate the electrical characteristics of the Collagen/HPMC/PVA/rGO scaffold for potential application as a biosensor in bone tissue engineering. The incorporation of rGO as a conductive nanomaterial successfully imparted electrical properties to the scaffolds, as evidenced by the appearance of redox peaks in CV analysis (Fajarani et al., 2025). These findings confirmed that rGO contributed to enhanced electron transfer behavior and improved electrochemical activity within the scaffold.

Conductive polymer-based scaffold incorporating PANI have also shown promising osteogenic potential. The research by Eskandani et al. developed alginate/PVA polymer scaffolds with the addition of PANI, which can improve and accelerate the regeneration process of defected bone. The scaffolds demonstrated proper electroactivities as well as conductivities that qualified them for bone tissue engineering, which requires electroconductivity. The MTT assay results revealed that the scaffolds have acceptable cytocompatibility and could improve MG-63 cells adhesion and proliferation (Eskandani et al., 2023). Similar electroactive behavior was also reported in PANI/PVA/nanostarch and PANI/PVA/nanocellulose scaffolds, both of which exhibited characteristic redox peaks during CV characterization, confirming their electroactive properties for tissue engineering applications (Dominic et al., 2023; Switha et al., 2022). Polypyrrole (PPy)-based conductive scaffolds have likewise demonstrated favorable electrochemical and biological performance. Research by Lou et al. developed HA/PDA/PPy scaffolds using conductive polymer materials capable of facilitating cell activity and signal transmission between scaffold matrices and cells. Electrochemical characterization using CV and EIS revealed stable electrochemical behavior, while biological evaluation demonstrated enhanced cell viability (Lou et al., 2023). Further research from the same group developed a PDA/PPy coating on HA scaffolds, demonstrating that the bone scaffolds exhibited redox peaks at the same potential after repeated doping/undoping cycles, indicating electrochemical stability. The scaffolds also exhibited no cytotoxicity before and after electrical stimulation, and cell growth increased significantly (T.-T. Li et al., 2023).

In addition to conductive polymers and carbon-based materials, electroactive polyurethane-based scaffolds have also been developed for bone regeneration. Electroactive polyurethane-aniline trimer (PUAT) fibrous membranes fabricated via electrospinning exhibited extracellular matrix-like structures, suitable biodegradation behavior, and excellent electroactivity. CV analysis demonstrated two characteristic redox peaks corresponding to electroactive transitions of the aniline trimer segment. The incorporation of electroactive components into PUAT scaffolds significantly enhanced rat mesenchymal stem cell (MSC) proliferation, osteogenic differentiation, angiogenic marker expression, and biomineralization potential (Sun et al., 2025).

Collectively, these studies demonstrate that conductive scaffolds fabricated using carbon-based nanomaterials, conductive polymers, and electroactive polyurethane systems exhibit favorable electrochemical characteristics and biological performance. Electrochemical analyses using CV and EIS consistently confirmed scaffold electroactivity, conductivity, and electrochemical stability, while biological evaluations demonstrated enhanced cell adhesion, proliferation, differentiation, and osteogenic potential. These findings indicate that the integration of electroactive biomaterials into scaffold matrices improves the physicochemical and biological properties of bone scaffolds and provides a promising platform for future biosensing and real-time cellular monitoring applications in bone tissue engineering. A summary of the electroactive conductive scaffolds, electrochemical characterization methods, and key findings discussed in this section is presented in Table 1.

Table 1. Electroactive Conductive Scaffold for Bone Tissue Engineering

No	Materials	Conductive Component	Electrochemical Characterization	Key Findings	Ref
1	Collagen/HPMC/PVA/rGO	rGO	CV	rGO incorporation induced electroactive behavior and redox activity suitable for conductive bone scaffolds	(Fajarani et al., 2025)
2	HA/PDA/PPy	PPy	CV, EIS	Electrochemically stable scaffold with enhanced cell viability and signal transmission	(Lou et al., 2023)
3	PPy/PDA/HA	PPy	CV, EIS	Stable redox activity and significantly improved cell growth	(T.-T. Li et al., 2023)
4	Alg/PANI/PVA	PANI	CV	Enhanced electroconductivity and cytocompatibility for bone regeneration	(Eskandani et al., 2023)
5	PANI/PVA/NS	PANI	CV	Electroactive scaffold with distinct redox peaks for tissue engineering applications	(Switha et al., 2022)
6	PANI/PVA/NC	PANI	CV	Conductive and electroactive scaffold behavior confirmed by electrochemical response	(Dominic et al., 2023)
7	PUAT	PUAT	CV	Electroactive fibers exhibited distinct redox peaks and enhanced rat MSC proliferation and osteogenic differentiation.	(Sun et al., 2025)

Alg = alginate, CV = cyclic voltammetry, EIS = electrochemical impedance spectroscopy, HA = hydroxyapatite, HPMC = hydroxypropyl methyl cellulose, MSC = mesenchymal stem cells, NC = nanocellulose, NS = nanostarch, PANI = polyaniline, PDA = polydopamine, PUAT = polyurethane-aniline trimer, PPy = polypyrrole, PVA = poly(vinyl alcohol), rGO = reduced graphene oxide

Conductive Scaffolds as Electrochemical Sensing Platforms

Besides functioning as electrically active biomaterials, conductive scaffolds have also been developed into electrochemical sensing platforms capable of monitoring cellular activities and tissue regeneration processes in real time. Initially, conductive materials were mainly utilized as passive conductive additives or coatings to improve electrical stimulation efficiency within scaffold constructs. In recent years, there has been growing research interest in developing conductive materials in three-dimensional biotechnological structures into complex electronic and sensing components (e.g., addressable electrodes and transducers) that actively monitor cellular signals and stimulate cells (X. Li et al., 2023).

The development of conductive scaffold-based sensing systems is strongly motivated by the limitations of conventional methods used for evaluating cell function within scaffolds. Traditional analyses, including gene expression analysis, histological staining, and fluorescent labelling of intracellular proteins, are generally invasive and destructive because they often require cell lysis, fixation, or extensive sample preparation. Consequently, these approaches are unsuitable for continuous and real-time monitoring applications. To overcome these limitations, smart conductive scaffolds have been developed to direct cellular activities while simultaneously monitoring cell adhesion, proliferation, and function in a non-destructive manner (De Maria et al., 2014). The electrochemical responsiveness of conductive materials has therefore attracted significant interest as a non-invasive detection strategy for continuously monitoring interactions between cells and scaffold interfaces (Huang et al., 2023).

Electrochemical sensing systems integrated into conductive scaffolds commonly rely on electroactive materials capable of converting biological responses into measurable electrical signals. Changes in cell adhesion, proliferation, differentiation, and extracellular matrix formation can alter electron transfer kinetics, impedance, or electrochemical current responses at the scaffold surface. As a result, electrochemical sensing approaches such as cyclic voltammetry (CV) and electrical impedance spectroscopy (EIS) have become important analytical methods for monitoring cellular behavior and scaffold performance in bone tissue engineering applications.

Conductive Scaffold-Based Electrochemical Sensors for Cell Monitoring

In the fabrication of electrochemical biosensors for cellular monitoring, conventional electrodes such as glassy carbon and Au electrodes have been widely used. However, these electrodes have disadvantages as working electrodes due to their surfaces being easily contaminated during electrochemical studies. Due to the complexity of biological samples, the maintenance process requires complex and time-consuming procedures, thereby limiting the practical application of cell-based biosensors. Therefore, the manufacture of low-cost, disposable electrodes for cell sensors is very important.

Several studies have demonstrated the effectiveness of conductive scaffolds for electrochemical monitoring of bone-related cellular behavior. Research by Li et al. developed an electrode device from a more flexible graphene material. Cell viability in the scaffold was higher and able to increase the proliferation of adipose-derived stem cells (ADSC) cultured on the scaffold while simultaneously functioning as electrochemical sensing platforms (J. Li et al., 2021). Similarly, Waiwijit et al. developed graphene/PDMS scaffolds as electrodes that demonstrated oxidation current signals in CV characterization that increased along with the increase in the number of cells. Therefore, this research has the potential to be used as a conductive substrate for cell-based electrochemical sensing (Waiwijit et al., 2016).

Cell viability and proliferation are among the most important parameters for evaluating scaffold biocompatibility and tissue regeneration potential. Conventionally, cell proliferation analysis relies on monitoring multiple cell cycles and biochemical assays, which are often labor-intensive and unsuitable for rapid assessment. Therefore, electrochemical biosensing systems have emerged as promising alternatives for rapid and non-destructive evaluation of cellular activity (Wei et al., 2019). Research by Madhurantakam et al. developed scaffold-integrated electrochemical biosensors capable of evaluating cancer cell proliferation through glucose monitoring. The developed biosensing system demonstrated several advantages, including fast response, simple instrumentation, low fabrication cost, easy preparation, high selectivity, and excellent sensitivity (Madhurantakam et al., 2017). These findings further support the feasibility of electrochemical scaffold-based biosensors for monitoring cellular metabolic activity in tissue engineering application.

CNT-based scaffolds have also demonstrated promising sensing capabilities for monitoring cell adhesion and proliferation. Research by De Maria et al. developed CNT/PLLA conductive scaffolds that functioned as EIS-based biosensors for evaluating cell adhesion and proliferation while simultaneously directing cellular growth (De Maria et al., 2014). Similarly, Zhong et al. developed an impedance cytosensor using MWCNT/chitosan scaffolds capable of quantitatively monitoring cell behavior related to cell adhesion, spreading, and proliferation without labelling. The scaffold also uses impedance to determine osteoblastic cell concentration and monitor interactions between cells and the scaffold (Zhong et al., 2022). These studies demonstrate the significant potential of CNT-integrated conductive scaffolds as multifunctional electrochemical sensing platforms for non-destructive cellular monitoring.

Electrochemical Monitoring of Osteogenic Differentiation and Bone Regeneration

Electrochemical sensing systems have also been explored for monitoring osteogenic differentiation. In bone tissue regeneration, mismatches between new bone formation and scaffold degradation can impair bone defect repair. Premature bone regeneration may lead to cyst formation and additional surgery, while early scaffold degradation compromises mechanical support. Moreover, donor-derived cells exhibit significant variability in proliferation and osteogenic potential, making real-time monitoring of cell mineralization essential. Huang et al. demonstrated that a scaffold containing 0.5% CNT provided electroconductivity for in vitro and in vivo monitoring of cell differentiation, enabling electrochemical detection of differentiation-related changes and highlighting the potential of electroactive scaffolds for tracking bone regeneration dynamics (Huang et al., 2023).

Similarly, another study was conducted by Lee et al., developed graphene/Au-modified ITO electrodes that enabled real-time and non-destructive monitoring of osteogenic differentiation in human mesenchymal stem cells (J. Lee et al., 2018). These findings indicate that conductive scaffold-based electrochemical sensing systems can provide continuous information regarding osteogenic progression without requiring destructive biological analyses.

Overall, the fabrication of conductive scaffold-based sensing systems commonly involves the integration of conductive materials with electrochemical platforms such as ITO, glassy carbon electrodes, and flexible graphene-based electrodes. Compared with conventional Au and carbon electrodes, flexible conductive scaffolds offer improved biocompatibility, reduced fouling effects, and better integration with biological tissues. Collectively, these studies demonstrate the growing potential of conductive scaffold-based electrochemical sensing systems for real-time and non-destructive monitoring of bone-related cellular behavior, including cell viability, proliferation, adhesion, and osteogenic differentiation. Although the number of reported studies remains relatively limited, current findings indicate that conductive scaffolds integrated with electrochemical sensing platforms represent a promising strategy for developing multifunctional smart biomaterials in bone tissue engineering. The current conductive scaffold-based electrochemical sensing scaffold used for monitoring bone-related cellular behavior discussed in this section is presented in Table 2.

Table 2. Conductive Scaffold-Based Electrochemical Sensing Platforms for Monitoring Bone Cell Function

No	Materials	Sensing Target	Cell Type	Detection Method	Key Findings	Ref
1	CNT/CMC	ALP and osteogenic differentiation	Human ADSCs	CV	Enabled real-time electrochemical monitoring of ALP expression and osteogenic differentiation	(Huang et al., 2023)
2	MWCNT/chitosan	Cell counting and monitoring cell growth	MC3T3-E1	EIS	Enabled quantitative label-free monitoring of osteoblastic cell adhesion and proliferation	(Zhong et al., 2022)
3	rGO/Alg	Cell immobilization on scaffolds and cell viability	ADSCs	CV, EIS	Enhanced ADSC proliferation while providing electrochemical sensing capability	(J. Li et al., 2021)
4	Graphene/Au	Osteogenic differentiation	Human MSCs	CV	Enabled non-destructive real-time monitoring of osteogenic differentiation	(J. Lee et al., 2018)
5	Graphene/PDMS	Cell viability and cell concentration on scaffolds	L929 fibroblast cells	CV	Generated oxidation current signals proportional to cell number	(Waiwijit et al., 2016)

ADSC = adipose-derived stem cells, Alg = alginate, ALP = alkaline phosphatase, CMC = carboxymethyl chitosan, CNT = carbon nanotube, CV = cyclic voltammetry, EIS = electrochemical impedance spectroscopy, MSC = mesenchymal stem cells, MWCNT = multi-walled carbon nanotube, PDMS = polydimethylsiloxane, rGO = reduced graphene oxide

CONCLUSION

Conductive smart scaffolds have emerged as promising biomaterials for bone tissue engineering by combining structural support, electrical stimulation, and electrochemical functionality. Conductive polymers, carbon-based nanomaterials, and hybrid composites have demonstrated significant potential to enhance osteogenic responses, including cell adhesion, proliferation, differentiation, and mineralization. This review highlights that, beyond improving scaffold performance, conductive materials offer a unique opportunity to develop integrated electrochemical sensing systems capable of non-invasive and real-time monitoring of cellular behavior during bone regeneration.

Despite these advances, most studies remain limited to electrochemical characterization and have not yet fully integrated sensing capabilities into scaffold platforms. Therefore, future research should focus on developing multifunctional conductive smart scaffolds that simultaneously support bone regeneration and enable continuous biosensing, thereby accelerating the development of next-generation intelligent biomaterials for precision bone tissue engineering.

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