eVitroKhem. 2025; 4:256
doi: 10.56294/evk2025256

REVIEW

Biointerfaces in sensors and medical devices: challenges, materials, and solutions for biological integration

Biointerfaces en sensores y dispositivos médicos: retos, materiales y soluciones para la integración biológica

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Cite as: Edet Usoro I, Akhigbe RO, Promise Ogolodom M, Shuaibu A, Emeka Ezugwu E, Titi Oyegbata O, et al. Biointerfaces in sensors and medical devices: challenges, materials, and solutions for biological integration. eVitroKhem. 2025; 4:256. https://doi.org/10.56294/evk2025256

Submitted: 20-10-2024 **Revised:** 12-02-2025 **Accepted:** 22-07-2025 **Published:** 23-07-2025

Editor: Prof. Dr. Javier Gonzalez-Argote

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ABSTRACT

Biointerfaces are strategic components in the design of medical sensors and devices, enabling functional interaction between electronic systems and biological tissues. This article examines their properties, materials, and clinical applications, with a focus on biocompatibility, cellular adhesion, electrical conductivity, and structural stability. Current approaches based on conductive hydrogels, nanocomposites with metal oxides, and intelligent coatings are reviewed, as well as their implications in implantable, wearable, microfluidic, and neural interface technologies. The study also addresses critical challenges such as miniaturization, immune response, and the integration of dynamic, stimulus-activated functions. It concludes that biointerfaces represent a key pathway toward the development of more precise, adaptive, and sustainable medical technologies, whose advancement will depend on interdisciplinary convergence among biomedical engineering, materials science, and emerging clinical needs.

Keywords: Biointerfaces; Medical Devices; Biocompatibility; Implantable Sensors.

RESUMEN

Las biointerfaces constituyen un componente estratégico en el diseño de sensores y dispositivos médicos, al permitir la interacción funcional entre sistemas electrónicos y tejidos biológicos. Este artículo analiza las propiedades, materiales y aplicaciones clínicas de estas superficies, con énfasis en la biocompatibilidad, la adhesión celular, la conductividad eléctrica y la estabilidad estructural. Se revisan enfoques actuales basados en hidrogeles conductores, nanocompuestos con óxidos metálicos y recubrimientos inteligentes, así como sus implicaciones en tecnologías implantables, portátiles, microfluídicas y neurointerfaces. También se abordan desafíos críticos como la miniaturización, la respuesta inmunológica y la integración de funciones dinámicas activadas por estímulos. El estudio concluye que las biointerfaces representan una vía clave para el desarrollo de tecnologías médicas más precisas, adaptativas y sostenibles, cuyo avance dependerá de la convergencia interdisciplinaria entre la ingeniería biomédica, la ciencia de materiales y las necesidades clínicas emergentes.

Palabras clave: Biointerfaces; Dispositivos Médicos; Biocompatibilidad; Sensores Implantables.

INTRODUCTION

Biointerfaces are a fundamental component in the functional architecture of biosensors, as they represent the area of direct contact between the device and the biological environment with which it interacts. They act as mediators of molecular interactions that enable the specific recognition of biomolecules such as proteins, nucleic acids, enzymes, or cells, hence their relevance in detection and diagnostic processes.[1]

From a technical point of view, the physical and chemical properties of the biointerface have a decisive influence on key performance parameters, including selectivity, sensitivity, detection range, and signal stability over time. Therefore, the detailed study and rational design of this interface are considered strategic aspects in the design and development of new-generation biosensors, which are aimed at high-precision clinical and diagnostic applications, thus responding to the current demands of biomedicine.[1]

The functional optimization of a biointerface requires precise control over the nature and specificity of the interactions that take place on its surface, which is crucial to ensuring the overall performance of the system. To this end, advanced materials are used, particularly surfaces functionalized with compounds such as gold, which are capable of facilitating selective immobilization of target molecules without compromising the structural integrity of the device. This approach not only improves the efficiency of biochemical recognition, but also minimizes external interference, reduces background noise, and significantly increases the signal-to-noise ratio. In this way, the biointerface is no longer considered a simple passive layer but is conceived as an active component of the sensor, essential for ensuring the fidelity and accuracy of the analytical response to complex biological stimuli.[1,2]

In implantable biomedical applications, the biointerface plays an even more critical role, as it must maintain constant, biocompatible interaction with the internal tissues of the recipient organism. After insertion, this surface not only ensures the physical integration of the sensor with the immediate biological environment, but also helps prevent adverse responses such as inflammation, fibrosis, or immune rejection, which could compromise the functionality of the implant. In this sense, the quality of the biointerface directly determines both the acceptance of the implant and the operational durability of the device, aspects that have a significant impact on therapeutic efficacy and the stability of long-term clinical monitoring. Designing biointerfaces that guarantee this structural and functional compatibility is therefore an essential requirement for the design and development of medical technologies that are safe and effective for patients.[1,3]

In the context of recent advances in biological interaction technologies, biointerfaces have become particularly important in the design of portable and implantable devices, particularly those linked to human-machine integration platforms. In this context, hydrogels are emerging as materials of choice due to their remarkable ability to establish a soft, adaptable, and electroconductive bond between living tissues and integrated electronic systems. Thanks to their multifunctional structure, these materials not only enable accurate and continuous transmission of physiological signals, but also help reduce the risk of local irritation and prolong the useful life of the implanted or portable device. Their incorporation into advanced biomedical sensors responds to the need to develop dynamic and responsive systems capable of maintaining sustained functional performance in complex and variable biological environments.[4,5,6]

Consequently, it is essential to further analyze biointerfaces as strategic components for the design and operation of state-of-the-art medical sensors and devices, as their direct influence affects the efficiency of biological recognition, the operational stability of systems, and biocompatibility with the physiological environment.[7,8] The progressive integration of these interfaces into wearable and implantable platforms and real-time continuous monitoring systems requires a critical and ongoing review of the material, functional, and technological approaches that support their development. Understanding the operational logic, coupling challenges, and innovation prospects associated with biointerfaces strengthens the relationship between biomedical engineering and life sciences, while helping to chart new paths for the creation of more accurate, safer, and more adaptable healthcare solutions for the human body.[9] Therefore, this article aims to examine current approaches and the main applications of biointerfaces in medical sensors and devices, emphasizing recent advances, the selection of materials with high biological compatibility, and the functional challenges faced by these systems in clinical, wearable, and implantable contexts.

METHOD

This work is based on a literature review aimed at systematizing current approaches, materials used, and functional challenges related to the design of biointerfaces in sensors and medical devices. To this end, a structured search strategy was carried out between March and June 2025, using as main sources the academic databases Scopus, PubMed, ScienceDirect, MDPI, ACS Publications, SpringerLink, as well as the meta-search engine Google Scholar, due to its wide coverage of indexed and open-access scientific literature.

The searches were carried out using combinations of keywords in English such as biointerfaces, implantable sensors, biocompatibility, conductive hydrogels, smart coatings, neural interfaces, and medical devices. Filters were applied by year of publication (2021–2025) and by document type (peer-reviewed articles with experimental results or technical analysis). A total of 48 scientific articles were selected, which were organized thematically and analyzed based on their contribution to the study of properties, clinical applications, and technological solutions in the field of biointerfaces. This process allowed us to identify common patterns, evaluate emerging trends, and precisely define the main lines of development in this area of biomedical research.

DEVELOPMENT

Among the materials used in the manufacture of biointerfaces for sensors and medical devices, conductive hydrogels stand out for their remarkable ability to combine electrical properties with a high level of biocompatibility. These three-dimensional gels exhibit an internal architecture that not only promotes efficient electrical signal conduction but also accurately reproduces the physical, chemical, and biological characteristics of native tissue. This mimetic ability enabl to act as conducive environments for cell growth by providing structural stability and environmental conditions suitable for sustained interaction with complex biological systems.[10,11]

Furthermore, their porous structure makes them highly effective substrates for the controlled release of bioactive molecules, significantly expanding their applicability in both therapeutic and diagnostic contexts. The possibility of customizing their properties according to the specific requirements of each biomedical application reinforces their role as strategic components within biointerfaces, enabling precise and sustained integration between the sensor and the surrounding physiological environment.[10,12,13]

Another particularly relevant approach in biointerface engineering is the use of nanocomposites that integrate conductive polymers with metal oxides, materials that exhibit enhanced electronic properties and high surface reactivity. In this regard, the study conducted by Badry R et al.[14] demonstrates that the incorporation of oxides such as magnesium oxide (MgO) and manganese II oxide (MnO) into the polyaniline structure significantly increases key parameters such as total dipole moment, band gap, and various molecular reactivity descriptors.[14,15,16]

These improvements translate into a greater ability of the material to transport charge in a stable manner, which is particularly advantageous in contexts where a precise and sustained signal is required, such as in implantable medical sensors. Furthermore, the high correlation observed between the experimental results and the spectroscopic calculations reinforces the reliability of the electronic behavior of these nanocomposites, consolidating their potential as functional elements in advanced biomedical systems.[17] Thus, the functionalization of conductive polymers with metal oxides not only significantly increases the electrochemical performance at the interface, but also favors a more harmonious integration with complex biological systems, which substantially expands their applicability in the development of biointerfaces with high sensitivity and prolonged durability.[14,18,19]

In the field of implantable sensors, biointerfaces have undergone a sustained evolution towards solutions that are progressively softer, more flexible, and more adaptable to the physiological environment, in response to the urgent need to reduce immune response and ensure stable and prolonged interaction with tissue. In this scenario, hydrogel-based nanocomposites are particularly relevant, given their high water content, intrinsic biocompatibility, and remarkable ability to replicate the texture and elasticity of living tissue. These materials, resulting from the integration of elastomeric matrices and functional nanocarriers, enable intimate and sustained contact between bioelectrodes and organic structures, thus facilitating the capture of high-resolution physiological data in real time. Added to this is their potential for functionalization, which enables a versatile platform for the design of implantable bioelectronic systems with adaptive properties, an essential condition for the prolonged monitoring of biological functions without inducing structural damage or altering the homeostatic balance of the tissue environment.[20,21]

At the same time, portable sensors and microfluidic devices have gradually established their presence in both the clinical and personal wellness sectors, thanks to their non-invasive nature and ability to provide real-time physiological monitoring. These technologies are integrated into a variety of formats ranging from smart accessories and functional garments to highly sensitive body patches, all designed with the aim of maintaining continuous contact with the skin surface without compromising user comfort at any time.[22,23]

In this context, biointerfaces play a fundamental role in ensuring stable transmission of bioelectrical signals while flexibly adapting to body movements, thus preserving the functional integrity of the system. At the same time, microfluidic devices integrate micrometer-scale channels capable of manipulating minute volumes of

https://doi.org/10.56294/evk2025256 ISSN: 3072-7944

biological fluids, enabling rapid and accurate analysis on compact platforms. This convergence of portability, high sensitivity, and compatibility with biological surfaces makes biointerfaces essential components for ensuring the functional efficiency of such systems.[22,23,24]

One of the most significant functional aspects in the design of biointerfaces lies in their ability to promote efficient cell adhesion, an essential condition for ensuring the effective integration of the sensor with biological tissues. In this regard, Nguyen et al.[25] show that the quality of the contact established between the device surface and the cells directly affects essential physiological processes such as differentiation, migration, cell cycle, and survival. Although reproducing the biochemical conditions of the extracellular matrix remains a considerable technical challenge, it is a key requirement for the development of a biologically active, functional, and durable interface.[25,26]

Biointerfacial materials that enable this type of interaction not only promote cell communication but also contribute to the functional durability of the sensor once implanted. Cell adhesion thus ceases to be a secondary phenomenon and becomes a key structural parameter for the success of biomedical applications based on sensors and soft electronic tissues.[25,27,28]

In addition to facilitating biological adhesion, biointerfaces must fulfill other critical functions, such as biocompatibility, electrical conductivity, and molecular detection capability. A representative example is polydimethylsiloxane (PDMS), widely used in implantable sensors and BioMEMS devices due to its low cytotoxicity, optical transparency, and adaptability to various structural configurations. When surface-modified, this material significantly improves its interaction with cells, allowing stable contact without inducing inflammatory responses. PDMS can also be combined with various conductive materials, including metal nanoparticles, carbon-based nanomaterials, and polymers with electrical properties, expanding its functionalities without compromising its mechanical flexibility. This remarkable versatility positions it as an ideal component for biointerfaces that simultaneously require biological compatibility, effective structural integration, and efficient transmission of electrical signals.[29,30]

In the context of continuous glucose monitoring, biointerfaces play a fundamental role by enabling efficient and stable interaction between the sensor and the patient's skin or subcutaneous environment. Currently, both transcutaneous sensors and long-lasting implantable versions are used, capable of transmitting real-time readings to mobile platforms. In both modalities, the quality of the biointerface is a key determinant of signal accuracy, sustained device adherence, and patient tolerance to prolonged use. However, these systems still face significant challenges related to component miniaturization, variability in measurement accuracy, time delay in detection, and the onset of skin reactions, especially in individuals with hypersensitivity to adhesives. Such limitations highlight the urgent need to develop more stable and biocompatible interfaces capable of maintaining prolonged functional contact without compromising tissue integrity or affecting user comfort.[31,32]

According to Yildiz[33], retinal prostheses made from aluminum antimony (AlSb) and lead sulfide (PbS) quantum dots, despite their efficiency in conducting electrical charge, cause reactive gliosis and structural damage in the implanted subretinal region. These adverse effects highlight the complexity of achieving functional integration without triggering inflammatory or degenerative processes in highly sensitive tissues such as the retina. Hence, one of the central challenges in this type of application is to achieve an adequate balance between miniaturization, stimulation capacity, and immunological compatibility, which requires further developments in materials and interface strategies that prioritize long-term tissue safety.[33,34,35]

In the recent development of biointerfaces for medical devices, near-infrared active coatings have emerged as a multifunctional solution with high clinical potential. These coatings allow the incorporation of advanced functions such as non-invasive monitoring, controlled drug release, and infection prevention through the disintegration of biofilms, all without compromising the biocompatibility of the device. Their ability to be remotely activated by light stimuli makes these surfaces active interfaces, capable of modifying their behavior in real time according to the physiological needs of the environment.[36,37] Similarly, it has been demonstrated that the combination of properties such as antimicrobial activity, wear resistance, and surface functionalization can be integrated into a single manufacturing step, thus optimizing process efficiency and reducing the complexity of clinical assembly. These advances position NIR coatings as key elements for the next generation of adaptive and dynamic biointerfaces in the medical field.[38,39,40,41]

On the other hand, smart coatings represent a class of functional interfaces capable of actively responding to environmental stimuli, significantly expanding their applicability in biomedical devices. Designed to detect specific conditions such as humidity, bacterial presence, or structural damage, these coatings adjust their properties in real time, improving both the durability of the device and its clinical performance. In particular, certain smart polymers have been designed to automatically release disinfecting agents upon detecting increases in humidity, generating a localized bactericidal response that contributes to infection control without external intervention. This adaptive functionality not only increases patient safety but also facilitates the creation of active surfaces with self-regulating capabilities, which is especially valuable in clinical settings where autonomous and effective solutions are required to minimize postoperative complications.[42]

https://doi.org/10.56294/evk2025256 ISSN: 3072-7944

In the recent development of biointerfaces for medical devices, near-infrared (NIR) active coatings have emerged as a multifunctional solution with high clinical potential. These coatings allow the incorporation of advanced functions such as non-invasive monitoring, controlled drug release, and infection prevention through biofilm disintegration, all without compromising the biocompatibility of the device. Their ability to be remotely activated by light stimuli makes these surfaces active interfaces, capable of modifying their behavior in real time according to the physiological needs of the environment. Similarly, it has been demonstrated that the combination of properties such as antimicrobial activity, wear resistance, and surface functionalization can be integrated into a single manufacturing step, thus optimizing process efficiency and reducing the complexity of clinical assembly. These advances position NIR coatings as key elements for the next generation of adaptive and dynamic biointerfaces in the medical field.[43,44,45]

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CONCLUSIONS

This article has described the main properties, clinical applications, and technological challenges associated with the development of biointerfaces for medical sensors and devices, addressing their role in the functional integration between electronic systems and biological tissues. Biointerfaces are emerging as key elements for ensuring biocompatibility, cell adhesion, electrical stability, and accuracy in physiological monitoring, both in implantable and portable platforms. Their effectiveness will depend not only on advances in smart materials and active structures, but also on their ability to adapt to dynamic en , minimize immune responses, and promote prolonged interaction without loss of functionality. Ultimately, the future of these technologies will require interdisciplinary approaches that integrate engineering, biology, and clinical design, aimed at creating safer, more personalized, and sustainable medical solutions.

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FUNDING
None.

CONFLICT OF INTEREST
None.

AUTHOR CONTRIBUTION
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