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Interdigitated electrodes: Innovation in the detection and monitoring of biological systems

Electrodos interdigitados: Innovación en la detección y monitoreo de sistemas biológicos

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INTERDIGITATED ELECTRODES: INNOVATION IN THE DETECTION AND MONITORING OF BIOLOGICAL SYSTEMS

ELECTRODOS INTERDIGITADOS: INNOVACIÓN EN LA DETECCIÓN Y MONITOREO DE SISTEMAS BIOLÓGICOS

ABSTRACT

Interdigitated electrodes are small devices with a geometry composed of two microelectrode arrays arranged in an alternating and parallel configuration, with micrometric spacing between them. This arrangement allows electrical signals to be applied and collected in a cyclic manner, making them useful tools for analyzing very small samples, such as microorganisms or other biological components. For this reason, they have been proposed as biosensors capable of detecting various biological phenomena. One of the most widely used is impedance, which reflects the opposition to the flow of electricity in a solution and can reveal important changes in cells, such as those associated with oxidative stress. Due to this monitoring capability, these sensors have potential applications in areas such as healthcare, the food industry, agriculture, and environmental monitoring.

Keywords: interdigitated electrodes, impedance, oxidative stress, biosensors, electrical signals

RESUMEN

Los electrodos interdigitados son dispositivos pequeños con una geometría particular. Están formados por dos microelectrodos dispuestos de manera alternada y paralela, separados por distancias micrométricas. Esta disposición permite enviar y recibir señales eléctricas de manera cíclica, lo que los convierte en herramientas útiles para analizar muestras muy pequeñas, como microorganismos u otros componentes biológicos. Por esta razón, se han propuesto como biosensores capaces de detectar distintos fenómenos biológicos, como cambios en la actividad celular o en el estado fisiológico de los organismos. Uno de los más utilizados es la impedancia, que refleja la resistencia al paso de la electricidad en una solución y puede revelar cambios importantes en las células, como aquellos asociados con el estrés oxidativo. Gracias a esta capacidad de monitoreo, estos sensores tienen aplicaciones potenciales en áreas como la salud, la industria alimentaria, la agricultura y el monitoreo ambiental.

Palabras clave: electrodos interdigitados, impedancia, estrés oxidativo, biosensores, señales eléctricas

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1. INTRODUCTION

Can you imagine a technology that evaluates and monitors biological systems in real time? Today, it is possible to observe how various biological systems respond to changes in their environment without having to label them with dyes or destroy them for analysis. Interdigitated electrodes are a tool that makes this possible. They are tiny metallic structures shaped like two microelectrodes arranged alternately and in parallel that function as highly sensitive electrical biosensors. From bacteria exposed to antibiotics to plant cells subjected to chemical stress, these devices detect subtle changes in real time through electrical properties such as impedance or capacitance, but how do they work, and why are they so useful in microbiology and molecular biology?

In particular, electrochemical biosensors measure changes in current, voltage, or impedance, making them highly accurate and efficient tools for detecting phenomena such as oxidative stress. This stress is caused by the presence of reactive oxygen species (ROS). ROS are active molecules that form naturally in cells and participate in normal processes; in excess, they can damage other molecules and cellular structures. Their common characteristic is that they contain oxygen and react easily with their environment, causing rapid changes in cells. Thanks to their ability to detect these species, electrochemical biosensors represent a promising alternative for applications such as environmental monitoring, the detection of pathogenic bacteria, and disease surveillance (Deshpande et al., 2021).

Currently, biosensors are used as a preliminary screening tool because they provide rapid, general results. However, these results require confirmation through more specific and robust laboratory methods. Nevertheless, today's biosensors face the challenge of achieving accuracy levels comparable to those of conventional laboratory equipment without sacrificing their sensitivity, which currently ranges between 70% and 80%. In addition, they must meet the growing demand for portable, affordable, and user-friendly devices. Overcoming these challenges will allow biosensors to become increasingly integrated into daily life, transforming the way we monitor and protect health, food quality, and the environment (Hicks et al., 2020).

2. DEVELOPMENT OF THE TOPIC

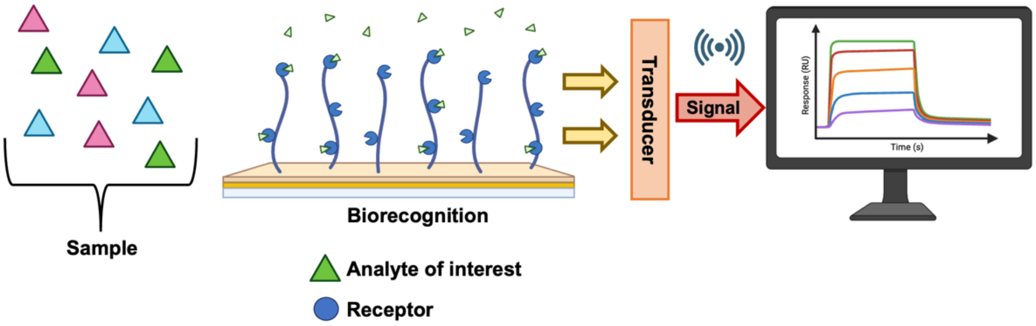
2.1. Key Features of biosensors

Biosensors are devices capable of detecting biological signals. A practical example of biosensors are blood glucose meters, which are widely recognized and used by the general public. These devices function as portable sensors that use an enzyme (usually glucose oxidase) in their test strips to measure blood sugar levels through electrochemical reactions. Biosensors are used in fields as varied as agriculture, environmental monitoring, disease diagnosis, and food safety, to name just a few examples. Depending on how they work, they can be classified as optical, thermal, electronic, gravimetric, and electrochemical (Mehrotra, 2016).

Biosensors work by using a biological component—such as enzymes, antibodies, or even cells—that specifically recognizes the substance to be detected. When this recognition occurs, a small change or reaction takes place that generates a signal. This signal is picked up by a transducer, which converts it into information that we can interpret and quantify. In this way, biosensors enable the rapid and accurate detection and analysis of various substances (Figure 1) (Bonetto et al., 2018).

Figure 1

Diagram of the components of a biosensor



Biosensors offer a promising alternative to conventional analytical methods due to their sensitivity, selectivity, reliability, long service life, low cost, and rapid response (Table 1).

Table 1

Key features of biosensors

Features	Description	References
Sensitivity	The continuous regeneration of the analyte in cyclic reactions increases the sensitivity of the electrode. A current of up to 10^{-10} A can be recorded using commercially available devices.	Wollenberger (1996)
Selectivity	Thanks to the components in the biosensor, interference with the reaction or the electrode caused by sample components of no interest can be eliminated.	Wollenberger (1996)
Reliability	This device features linearity, which contributes to the accuracy of the measured results.	Naresh y Lee (2021)
Lifespan	Improvements in materials and in the immobilization of the biocomponent have made it possible to increase the device's lifespan and signal stability.	Turner (2013)

Table 1
Key features of biosensors

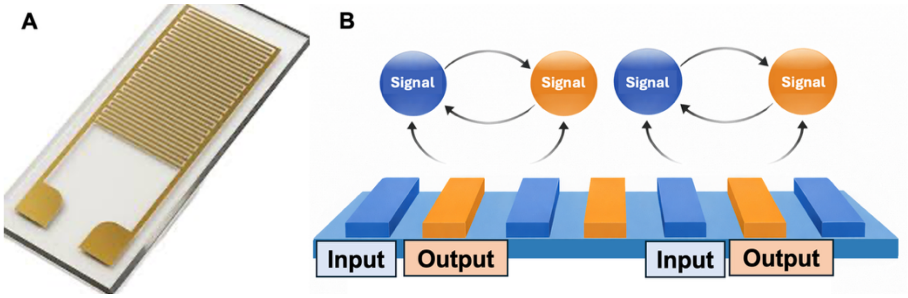
Features	Description	References
Low cost	Miniaturization and large-scale production have helped reduce costs compared to conventional instrumental methods.	Turner (2013)
Analysis time	Their ability to deliver rapid results, enabling real-time or near-point-of-care analysis. This feature makes them an attractive alternative to laboratory techniques that involve longer and more complex procedures.	Turner (2013)

2.2. ¿What are interdigitated electrodes?

An interdigitated electrode consists of two sets of metal microelectrodes arranged alternately and in parallel (Figure 2). When an electrical signal is applied between the two sets, an electric field is generated on the sensor surface. When cells or microorganisms are present on this surface, they alter that electric field. These alterations result in measurable changes in electrical parameters. Essentially, the system functions as an invisible scale that detects variations in: the number of adherent cells, membrane integrity, metabolite production, biofilm formation, and changes in cell morphology (Mazlan et al., 2017).

The interdigitated array (IDA) electrode is a small device designed to study what happens in a sample using minimal amounts of liquid. This makes it particularly valuable when the sample is scarce or difficult to obtain. At first glance, the IDA looks like a pattern made up of many very thin lines placed side by side. In reality, it consists of dozens of small pairs of electrodes; the number of pairs can vary depending on the electrode design. Each pair works together: One provides the input signal and the other receives the output signal (Figure 2) (Odijk et al., 2008).

Figure 2
Interdigitated electrode



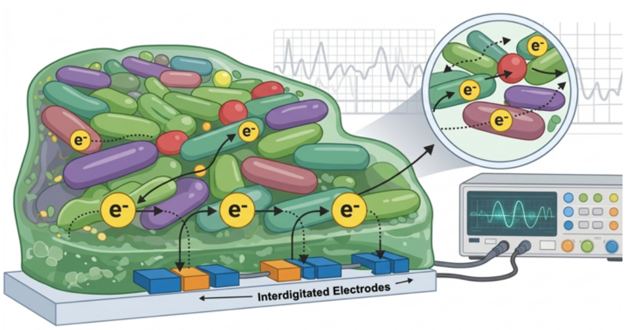
Note. (A) Image of an actual interdigitated electrode, consisting of small interwoven metal lines on a solid surface. (B) Schematic illustration of how it works: each pair of electrodes works together, with one sending an electrical signal and the other receiving it. This exchange occurs continuously back and forth, allowing for the detection of very small changes in the sample placed on the device.

When a very weak electrical signal is applied, it causes small changes in the substances present in the sample. The first electrode triggers this transformation, and the second detects it. This exchange occurs repeatedly, as if the signal were traveling back and forth between the two, which amplifies the process and makes it easier to measure. Thanks to this design, the IDA can detect very small changes in the sample, even when working with tiny volumes. That is why it has become a key tool for studying chemical reactions, analyzing compounds, and developing biosensors capable of responding to changes in cells and microorganisms. In short, it is a microscopic structure that harnesses electricity to reveal invisible processes, using just a few drops of sample (Odijk et al., 2008).

Due to their high sensitivity, IDA electrodes are useful for studying complex biological systems. In living systems, such as bacterial biofilms (dense layers with a 3D structure that microorganisms form on a surface), this type of electrode allows us to observe how electricity flows through the microbial community (Figure 3). Some bacteria can move small electrical charges between one another, as if they were connected by an internal network. When this occurs, the biofilm becomes more *conductive*. That is, it facilitates the passage of electricity. This change can be clearly detected using these sensors (Zazueta-Gambino et al., 2020).

Figure 3

Illustration of a bacterial biofilm formed on an interdigitated electrode



Note. Bacteria, arranged in a three-dimensional structure, exchange small electrical charges with one another, which facilitates the flow of electricity through the community. These changes can be detected through subtle electrical signals that allow researchers to analyze—without altering the sample—how the bacteria interact and how they contribute to the system's electrical behavior.

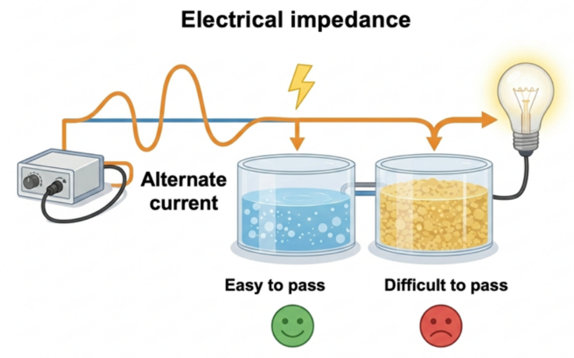
Furthermore, by working with subtle, constantly changing electrical signals, interdigitated electrodes allow for a more detailed analysis of the system's response. This helps distinguish which part of the signal originates from the biofilm, which is related to the contact between the cells and the electrode, and which depends on the surrounding fluid. Taken together, this tool provides a better understanding of how bacteria organize and interact when living in a community, without the need to alter or destroy the sample (Zazueta-Gambino et al., 2020). All this information is derived from how the system resists or responds to the passage of an electric current, a property known as impedance. Analyzing these changes in impedance is precisely the basis of impedance biosensors, which allow for the detection and monitoring of biological processes in real time.

2.3. Impedance biosensors

Electrical impedance is the resistance a system offers to the flow of an alternating current. In simple terms, it is like measuring how difficult it is for electricity to pass through a medium (Figure 4). Impedance biosensors assess how the total resistance to the passage of an electrical signal changes when a biological interaction occurs in the system (Grieshaber et al., 2008).

Figure 4

Conceptual illustration of electrical impedance



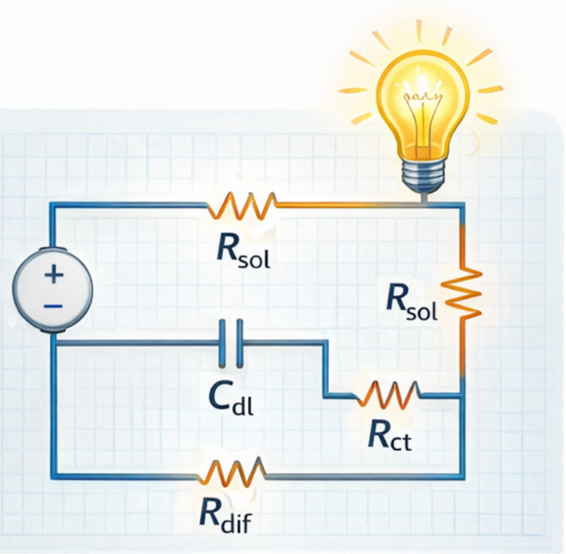
Note. Alternating current attempts to pass through different media: when the path is unobstructed, electricity flows easily; when it encounters greater resistance, the flow is impeded.

However, this opposition does not depend on a single process, but rather on the combined effect of several phenomena occurring simultaneously. When an electrochemical reaction takes place in a biosensor, what is actually happening is an exchange of electrons at the electrode surface. However, this process does not depend on a single factor; rather, several phenomena occur simultaneously: the ease with which the solution conducts electricity, the way molecules adhere to the surface, the exchange of charges at that point of contact, and the movement of molecules from within the solution to the electrode (Grieshaber et al., 2008).

To understand everything that happens in that tiny space where the electrode comes into contact with the solution, scientists use a very useful tool: they imagine the system as if it were an electrical circuit (Figure 5). Not because there are actually wires and electronic components inside the liquid, but because this analogy allows them to better organize and describe what is happening. When the sensor sends an electrical signal, the current encounters various *obstacles* in its path (Mazlan et al., 2017).

Figure 5

A simplified model that represents the sensor's operation as if it were an electrical circuit



Note. Each element represents a real-world process: the resistance of the liquid to the flow of current (Rsol), the interaction of molecules at the electrode surface (Rct), the temporary accumulation of charges at that surface (Cdl), and the rate at which molecules arrive from the solution (Rdif).

These *obstacles* can be represented as different components within that equivalent circuit, each associated with a specific process. Part of this resistance comes from Rsol: depending on its composition, electricity can flow more or less easily. Another part occurs right at Rct, where molecules interact and, in some cases, exchange small charges. If this process is fast, the current flows more easily; if it is slow, it offers greater resistance. Furthermore, before reaching the electrode, the molecules must move from inside the solution to the Rdif. If that movement is fast, the signal changes in one way; if it is slower, it changes in another. Even the momentary accumulation of charges on the surface also influences the Cdl (Mazlan et al., 2017).

The circuit-based model combines all these effects into a single, simple diagram (Figure 5). Each component of the circuit represents one of these real-world processes: the flow of current through the liquid, surface interactions, and molecular motion. By analyzing them together, researchers can interpret the impedance—that is, how difficult it is for electricity to pass through the system and which processes are contributing to that difficulty (Yuan et al., 2010).

This way of interpreting the system highlights a key advantage of impedance over other simpler electrical measurements. Unlike simple resistance, which only measures how much the flow of current is impeded, impedance offers a more comprehensive view, as it takes into account various factors that influence how the electrical signal behaves within the system. In other words, it captures how much the electricity is *slowed down*, as well as how the system responds to changes in the applied signal (Mazlan et al., 2017). Impedance in microbiological systems reflects the electrical properties of cells, particularly the cell membrane, which acts as a frequency-dependent capacitor. Changes in impedance allow microorganisms to be differentiated based on their cellular structure and cell wall composition. Furthermore, electrochemical impedance is a non-invasive and rapid tool for characterizing bacteria in real time (Christy Dasmasela et al., 2024).

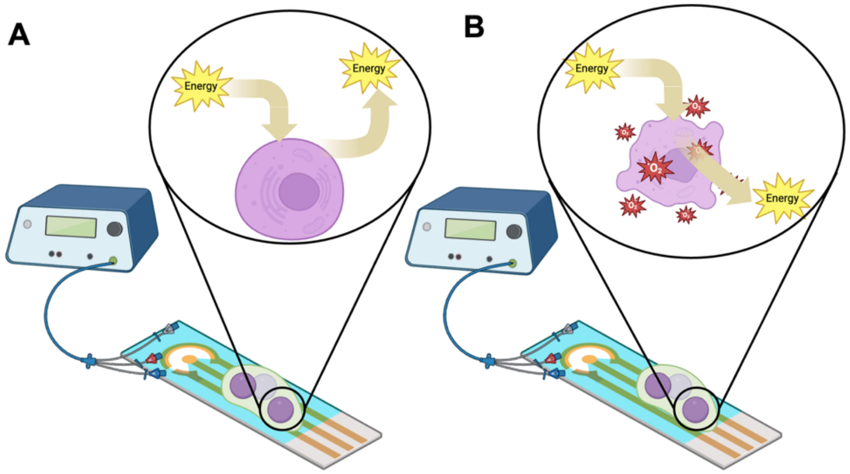
Impedance biosensors use a small electrode system to which a controlled alternating electrical signal is applied, and the system's response is recorded. By comparing the input signal with the output signal, it is possible to determine the impedance—that is, the extent to which the system resists the passage of that signal. Since the electrical response is not immediate but exhibits slight delays, the impedance changes depending on the frequency of the applied signal. By analyzing this response at different frequencies, researchers can distinguish various phenomena occurring at the electrode surface, such as the binding of molecules or changes in the sensor's biological layer (Randviir & Banks, 2022).

These changes originate primarily in a key region of the biosensor known as the electrode–bioreceptor interface, which is the point of contact between the biological world and the electronic world of the sensor. At this interface, the electrode is coated with a biological layer—such as enzymes, antibodies, DNA, or even cells—that has the ability to specifically recognize a target molecule. When the analyte binds to the bioreceptor, not only does a biological interaction occur, but physical and electrical changes are also generated in that thin surface layer. The distribution of charges, the organization of molecules, or the ease with which the electrical signal passes through that region may be altered. These small changes alter the way the applied electrical signal behaves in the system. In impedance biosensors, these variations are reflected as changes in the resistance to the passage of the electrical signal. Thus, what began as a microscopic event—the binding of two molecules—ends up becoming a measurable signal that can be recorded and analyzed (Mamouni & Yang, 2011).

In particular, this phenomenon occurs when the bioreceptor consists of cells or when they adhere directly to the electrode surface. Under these conditions, the cells alter the way electricity can pass through the system. As they accumulate, they act as small barriers that impede the flow of current, change the way electricity circulates through the liquid, and alter how charges are distributed on the surface. For example, if bacteria form a biofilm (that dense, organized layer they create when living in a community), the passage of electricity becomes more difficult. Conversely, if an antibiotic damages their membranes, the current can flow more easily. When the cells die, the electrical signal also changes in a specific way. This allows us to detect that something has changed in the state of the microbial community (Figure 6) (Deshpande et al., 2021; Randviir & Banks, 2013).

Figure 6

Illustration of cell signals



Note. (A) When bacteria form a biofilm, they create a layer that covers the electrode and hinders the flow of electricity, acting as a barrier. (B) When the cells are damaged, that barrier weakens and electricity can flow more easily.

It is precisely this ability to detect direct changes in the system's electrical behavior that gives rise to one of the main advantages of impedance biosensors, as they do not require the use of additional labels. In many traditional methods, it is necessary to add fluorescent substances, enzymes, or chemical compounds that *label* the molecule of interest in order to detect it. In contrast, impedance biosensors directly detect the electrical changes that occur when the analyte binds to the bioreceptor. This simplifies the procedure, reduces costs, and eliminates additional preparation steps. Another important advantage is that they enable real-time analysis. This means that the sensor can record changes as they occur, without having to wait for a reaction to finish or perform subsequent processing (Mazlan et al., 2017).

In this way, it is possible to observe how molecular interactions unfold second by second, which is particularly useful in affinity studies, biological monitoring, or the early detection of contaminants or pathogens. Taken together, these characteristics make impedance biosensors sensitive, fast, and efficient tools for converting biological events into measurable electrical signals. Furthermore, when interdigitated electrodes are combined with more detailed electrical measurements, it is possible to observe not only the presence of reactive molecules but also how these molecules affect the behavior of the biofilm. The accumulation of oxidizing species can alter the bacterial membrane, modify the structure that holds the bacteria together, and change their internal activity. All of this influences the way electricity flows through the microbial community (Shao & Xiao, 2020; Sun et al., 2015).

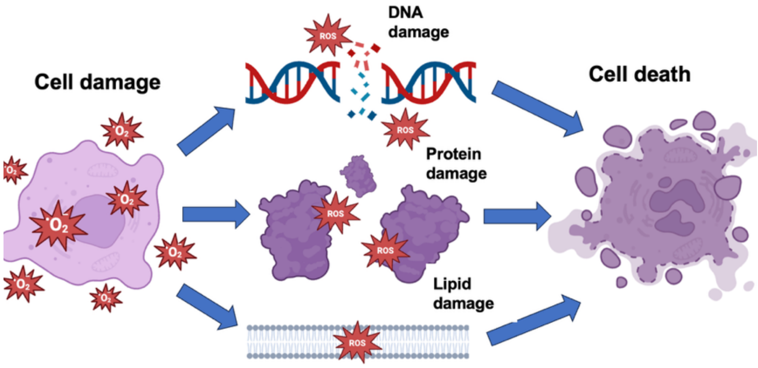
These changes are reflected in the electrical signal recorded by the sensor, showing variations that indicate how the system is changing. Thus, the interdigitated electrodes not only allow us to detect these reactive molecules, but also to monitor in real time how oxidative stress affects the way bacteria exchange charges and how the bioelectric system functions as a whole (Shao & Xiao, 2020; Sun et al., 2015).

2.4. Monitoring of oxidative stress

Electrochemical sensors are very useful tools for detecting highly reactive molecules that occur naturally during various biological processes. These substances can cause what is known as oxidative stress, a condition that disrupts the internal balance of cells. Under normal conditions, cells have their own mechanisms to maintain this balance and protect their vital functions. However, when the amount of these molecules exceeds the cell's defense capacity, damage can occur to important components such as proteins, lipids, or even genetic material, which in extreme cases can lead to cell death (Figure 7). Measuring oxidative stress is important because it allows us to determine a cell's state and understand whether it is functioning properly or is under adverse conditions. This information can be key to studying various diseases and assessing an organism's overall health (Deshpande et al., 2021; Li et al., 2020).

Figure 7

Illustrated diagram showing how reactive molecules can affect a cell



Note. These species can damage various essential components, such as genetic material, proteins, and the lipids that make up the cell membrane. When the damage accumulates and exceeds the cell's ability to repair itself, it can ultimately trigger cell death.

Oxidative stress can be studied not only indirectly in the laboratory. Today, it is possible to monitor it almost in real time thanks to electrochemical biosensors. One example of this is the development of flexible sensors capable of measuring molecules such as nitric oxide, a substance that plays a role in normal bodily processes but which, at high concentrations, may be associated with inflammation and cellular damage. In this type of study, researchers design small, biocompatible devices that can be placed in direct contact with living tissue. They are first tested on cultured cells to observe how the levels of these molecules change under different conditions (Li et al., 2020).

They are then tested in animal models, such as rabbits, where the sensor can be placed in specific areas. For example, inside a joint, to continuously monitor the chemical changes associated with inflammatory processes. The ability of these devices to transmit information continuously allows for monitoring the evolution of tissue condition without resorting to repetitive or invasive procedures. Thus, electrochemical biosensors not only help to better understand oxidative stress but also represent a promising tool for the early diagnosis and monitoring of diseases related to cellular damage (Li et al., 2020).

Given that oxidative stress plays a key role in the progression of various diseases, efforts to modulate ROS levels in different clinical settings for therapeutic purposes have intensified. In this regard, both conventional therapies and emerging strategies have recently been evaluated using electrochemical techniques, which directly and sensitively analyze changes in these *redox* mediators (Deshpande et al., 2021).

However, electrochemical biosensors are not limited to healthcare applications. In recent years, these techniques have also begun to be combined with microorganisms for environmental analysis and monitoring. Certain bacteria can be engineered to react specifically to the presence of specific pollutants, allowing the biosensor to generate a clearer and more accurate signal. Furthermore, these systems can be adapted to different environments, such as drinking water, wastewater, soil, or sediments. This is possible because many bacteria alter their activity when they come into contact with pollutants. By detecting these changes, the biosensor can convert them into measurable electrical signals, thereby facilitating the identification and monitoring of environmental pollution (Haddour & Azri, 2023).

Recent literature shows that electrochemical biosensors based on electroactive bacteria have been used to detect a wide variety of environmental contaminants. Among the compounds evaluated are heavy metals such as chromium (Cr VI), cadmium (Cd II), zinc (Zn II), mercury (Hg II), copper (Cu II), and palladium (Pd II); organic compounds such as 4-nitrophenol, 2,4-dichlorophenol, atrazine, formaldehyde, and avermectin; antibiotics such as neomycin sulfate; as well as complex mixtures such as mining effluents, wastewater, acid rain, and even urine samples (Haddour & Azri, 2023).

Regarding sensor configuration, most systems use bioanodes or biocathodes integrated into microbial fuel cell (MFC) configurations or three-electrode electrochemical (TEC) systems. The most commonly used materials for electrodes include carbon cloth, carbon filters, graphite, and printed electrodes (SPE), due to their good conductivity and compatibility with microbial growth. In most cases, microorganisms are immobilized through the direct growth of biofilms on the electrode surface or through bacterial adsorption (Haddour & Azri, 2023).

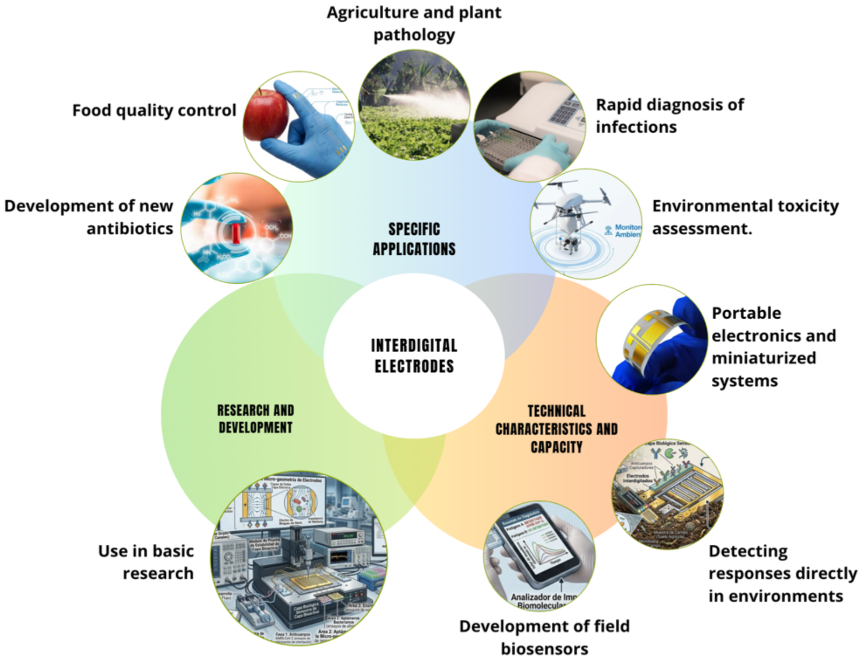
The reported detection signals include changes in current, voltage, electromotive force, and even photoelectric responses. These systems have demonstrated response times ranging from seconds or minutes to several hours, depending on the contaminant and the sensor configuration. The reported detection limits are competitive, with values reaching very low concentrations for certain metals and organic compounds. Furthermore, the operational lifespan of the devices can range from days to several months, and even up to a year in some cases, demonstrating their potential for continuous monitoring. Taken together, these results demonstrate that electrochemical biosensors based on electroactive bacteria constitute a versatile and sensitive strategy for environmental monitoring, with applications ranging from the point detection of specific contaminants to the assessment of toxicity in complex matrices (Haddour & Azri, 2023).

2.5. Applications

Interdigitated electrodes are not only used in basic research. They also have applications in: rapid diagnosis of infections, assessment of environmental toxicity, food quality control, development of new antimicrobials, agriculture, and plant pathology. Their integration with portable electronics and miniaturized systems paves the way for field biosensors capable of detecting microbial responses directly in agricultural or clinical settings (Figure 8).

Figure 8

Schematic diagram illustrating the applications of interdigitated electrodes



Many of these applications rely on the measurement of electrical impedance, a technique that, in recent years, has become an increasingly popular tool for studying various biological phenomena. This technique allows, for example, the monitoring of enzyme-catalyzed reactions, the detection of recognition between biomolecules such as proteins, nucleic acids, antibodies, or even whole cells, as well as tracking bacterial growth or identifying their presence in aqueous media. The use of interdigitated electrodes combined with impedance measurements has facilitated the development of smaller, more portable devices, in addition to improving detection sensitivity. Another important advantage is that these systems can be manufactured with relative ease, which facilitates their application in various areas of research and diagnostics (Varshney & Li, 2009).

Interdigitated electrodes can also be used to monitor food quality. Several studies have shown that these devices can detect pathogenic bacteria such as *Escherichia coli* and *Salmonella typhimurium* in products like raw chicken. In some cases, it has been possible to identify them at concentrations as low as 10 cells per milliliter in less than an hour. Due to their selective recognition capability, this type of biosensor can also be used to identify and monitor other pathogens present in food. Furthermore, one of their advantages is that they can distinguish between live and dead bacteria, providing more accurate information about the product's microbiological status (Abdullah et al., 2019).

Another area where these sensors show great potential is environmental monitoring. Interdigitated electrodes can be integrated into devices capable of detecting contaminants in water. For example, some sensors have been designed to identify ions such as cesium, an element found in industrial or nuclear waste. By measuring changes in the system's conductivity, these devices can detect variations in contaminant concentration, opening the door to continuous water quality monitoring (Nickson et al., 2010).

In the agricultural sector, interdigitated electrodes have been used to monitor plant physiological parameters. One example is the development of flexible sensors capable of measuring the relative water content in tobacco leaves in real time during the drying process. These types of sensors make it possible to track changes in leaf moisture and optimize drying conditions, which can improve product quality and facilitate process automation (Cheng et al., 2025).

Overall, interdigitated electrodes, combined with impedance measurements, represent a versatile and highly sensitive tool for analyzing biological, environmental, and food systems. Their ability to detect electrical changes associated with microscopic processes, along with their potential for miniaturization and real-time application, positions them as a promising technology in the development of modern biosensors. As these tools continue to evolve, their use can be expanded into various fields, from diagnostics to precision agriculture. In this context, it is important to reflect on their scope, advantages, and limitations, as well as their role in the development of new monitoring and control strategies.

3. CONCLUSIONS

Interdigitated electrodes demonstrate that electricity can serve as a language for understanding biology. Every change in a cell—whether damage, growth, or stress—leaves a measurable electrical signature. In an era where rapid, sensitive, and non-invasive monitoring is sought, these devices represent a fascinating convergence of microbiology, molecular biology, and electrochemistry. Essentially, they are small metallic structures that allow us to *listen* to what cells say when their environment changes. Although they are currently presented as a promising alternative to conventional methods, much remains to be understood about the phenomena occurring at these interfaces and, above all, the potential these devices could reach for evaluating and monitoring various biological processes.

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