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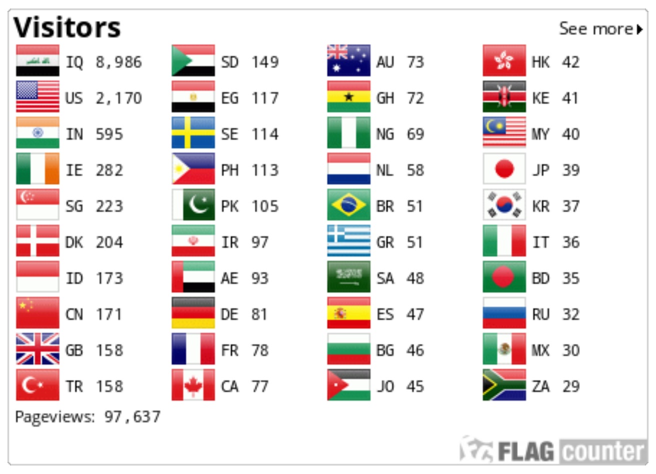

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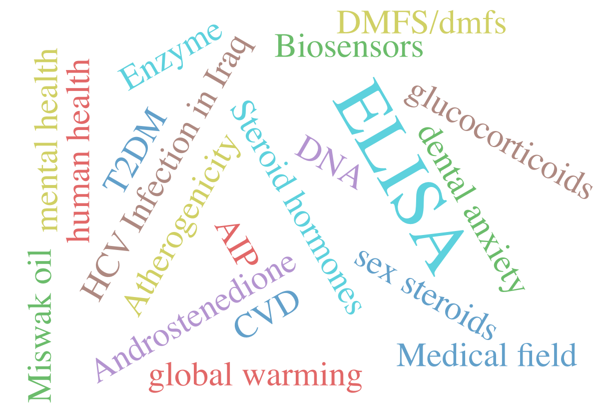

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Biosensors applications in the medical field: A Review

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ABSTRACT: Biosensors are analytical instruments that combine biological recognition components with transducers to identify and measure analytes, vital in medical diagnostics, environmental surveillance, and industrial uses. This review examines advancements in biosensor technology, emphasizing their classification according to detection mechanisms, such as electrochemical, optical, piezoelectric, and thermal sensors. Biosensors are extensively utilized in the medical domain for glucose monitoring in diabetic individuals, early cancer detection via biomarker analysis, and swift identification of pathogens in infectious diseases. The biosensors are crucial in monitoring endocrine-disrupting chemicals (EDCs), and evaluating environmental pollutants. Recent advancements encompass the incorporation of wireless monitoring systems, artificial intelligence, and nanotechnology, markedly improving biosensor sensitivity, specificity, and real-time data processing capabilities. Miniaturized biosensors and wearable devices have transformed personalized medicine by facilitating continuous health monitoring. The innovations in enzyme-based biosensors, DNA biosensors, and immunosensors broadened their utility in disease diagnosis and pharmacological research. Issues such as stability, reproducibility, and biocompatibility continue to be pivotal domains of investigation. The future of biosensors is characterized by intelligent, multiplexed, and highly portable devices featuring enhanced real-time analytical capabilities. As biosensor technology advances, its significance in medicine and industry will increase, providing swift, economical, and precise detection instruments for various applications.

Keywords: Biosensors, DNA, Medical field, enzyme

1. INTRODUCTION

Biosensors represent analytical devices that convert biological interactions into measurable electrical signals. To ensure reliable performance, effective biosensors must demonstrate high precision, resistance to environmental fluctuations such as pH and temperature, and the capability for repeated use. The term “biosensor” was initially introduced by Cammann, with its definition later formalized by the International Union of Pure and Applied Chemistry (IUPAC) [1].

Developing biosensors involves a multidisciplinary approach that integrates principles from biology, chemical engineering, and materials science. Based on their functional mechanisms, biosensors are commonly divided into three main categories: biocatalytic sensors, which utilize enzymes; affinity-based sensors, which involve antibodies or nucleic acids; and microbial sensors, which rely on the activity of whole microorganisms [2].

The conceptual foundation for biosensors dates back to the 1960s through the pioneering work of Clark and Lyons. Since then, various types have emerged, including enzyme-based sensors, immunosensors, thermal sensors, and piezoelectric biosensors, each designed for specific applications [1, 3].

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Notably, Updike and Hicks introduced the first enzyme-based biosensor in 1967, employing immobilization techniques such as van der Waals adsorption, ionic interaction, and covalent attachment [4]. Commonly used enzymes include oxidoreductases, polyphenol oxidases, peroxidases, and amine oxidases.

Tissue-based biosensors, derived from plant or animal sources, typically function through interactions with substrates or inhibitors. For instance, Rechnitz developed an early tissue-based sensor to detect arginine concentrations using biological tissues. Additionally, organelle-based sensors utilize components like chloroplasts, mitochondria, and microsomes. While these systems offer high specificity, they often suffer from slow response times and limited sensitivity. The introduction of immunosensors marked a significant advancement, capitalizing on the high specificity of antibody-antigen interactions to detect toxins, pathogens, or other immune-related molecules within biological samples [5].

The fundamental principles of a biosensor's functionality are shown in Figure 1. Like an enzyme, a particular element identifies a certain unknown, and a sensing element converts the alteration into biological molecules into a signal of electricity. The aspect is individual to the chemical to which it responds [6]. It fails to identify additional analytes. The biosensors may be categorized based on the transmitting technology, comprising resonant biosensors, optically activated biosensors, thermal sensing biosensors, and electrochemical biosensors [7].

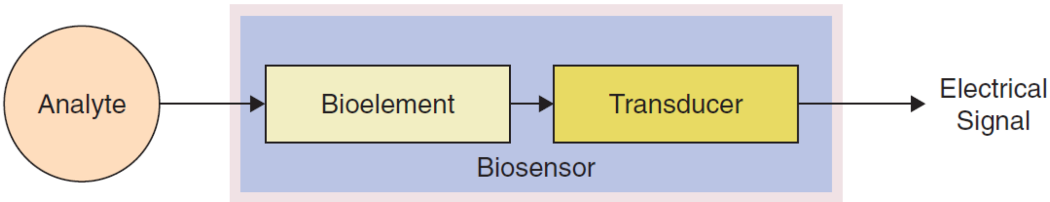

FIGURE 1. - A schematic representation of biosensors [8]

Figure 1 illustrates the fundamental working principle of a biosensor. Initially, the analyte interacts specifically with a bio element, such as an enzyme or antibody, facilitating selective detection. Subsequently, this biological interaction is converted by a transducer into an electrical signal. Thus, the biosensor effectively translates biochemical reactions into measurable electrical outputs, enabling precise quantification and analysis of biological substances in various practical and diagnostic applications.

The biosensors have diverse uses in healthcare, industrial, and military fields, as seen in Figure2 [9]. The biosensors possess substantial potential for industrialization across several applications, including biosensor-based equipment in beverages and food manufacturing, environmental monitoring, and sensitive medicinal analytic tools. Nonetheless, industry acceptance remains sluggish due to many obstacles to technology. For instance, the coexistence of microorganisms with semiconductor components presents a significant challenge regarding biosensor infection. DNA biosensors were created because a single-stranded nucleic acid molecule can detect and bond to its strand in a sample. Adding biosensor materials to a physical transducer creates thermal or calorimetric biosensors [8].

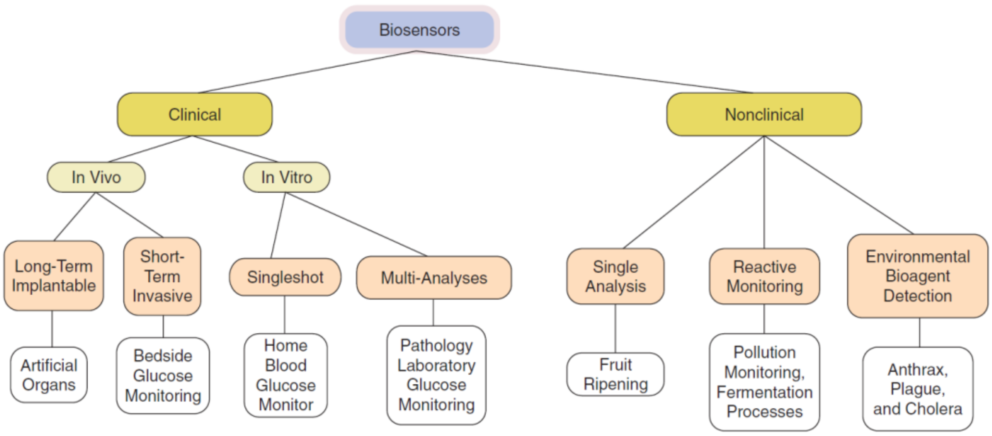

FIGURE 2. - Potential applications of biosensors

Figure 2 illustrates the primary classification of biosensors into clinical and nonclinical categories. Clinical biosensors are subdivided into in vivo systems, such as long-term implantable devices (e.g., artificial organs) and short-term invasive tools (e.g., bedside glucose monitors), and in vitro systems, which include single-use sensors for personal monitoring and multi-analyte devices utilized in clinical laboratories for comprehensive diagnostics, such as blood glucose assessments.

On the other hand, nonclinical biosensors are applied in a broader range of environmental and industrial settings. These include single-analyte applications, such as monitoring fruit ripening; dynamic or reactive systems for tracking fermentation processes and pollution levels; and biosensors dedicated to the detection of environmental bioagents, including pathogenic threats like Bacillus anthracis (anthrax), Yersinia pestis (plague), and Vibrio cholerae (cholera).

Optical biosensors consist of an electromagnetic source and additional electronic parts that generate a beam with specific characteristics, sending the resulting light toward a modifying agent, an altered sensing head, and a device that detects light [9].

The advent of green fluorescent protein (GFP), along with its evolved auto-fluorescent gene variants and genetically engineered fusion reporters, significantly advances the field of genetically encoded biosensors. These biosensors offer intuitive design, facile genetic manipulation, and efficient integration into living cells, enabling real-time monitoring of intracellular processes. Their modular nature facilitates customization for specific biological targets, making them invaluable tools in cellular imaging, functional genomics, and synthetic biology [10]. The single-chain Förster Resonance Energy Transfer (FRET) sensor is an illustrative example of genetically encoded biosensors. This system typically consists of a pair of auto-fluorescent proteins (AFPs) capable of transferring energy between each other when brought into proximity, thereby enabling the detection of molecular interactions or conformational changes. Multiple strategies are employed to optimize FRET signal dynamics, including adjustments in fluorescence intensity, emission ratios, or fluorescence lifetime measurements. In parallel, synthetic peptide- and protein-based biosensors are developed using advanced chemical synthesis and enzymatic labeling with synthetic fluorophores. Unlike genetically encoded FRET systems, these biosensors function independently of endogenous fluorescent proteins, providing increased design flexibility. Moreover, they offer enhanced signal-to-noise ratios and sensitivity by integrating features such as chemical quenchers and photoactivatable groups. These capabilities make them particularly valuable for monitoring dynamic biochemical activities and regulating molecular targets with high spatial and temporal resolution [7, 9].

2. BIOLOGICAL SENSORS AND BIOANALYTICAL METHODS

Biosensors can be distinctly distinguished from bioanalytical procedures and bioassays. Bioassays often encompass many processing stages, such as incorporating another reagent (e.g., enzymes or substrates). While most biosensors identify the individual analytes rather than a combination of several analytes, advancements in novel methods, such as array configurations. Generally, the application of biological sensors does not rival bioanalytical approaches. Biosensors are primarily engineered as the initial filter for collection screening through regulatory bodies. Consequently, the primary objective is to decrease the expenses associated with monitoring programs [2, 11].

While cytotoxicity experiments employing animals and larger organisms supply enhanced importance for humans compared to biosensors, they are accompanied by several restrictions in their application for cytotoxicity and mutation evaluations. These limits encompass time usage, expense, and spatial needs. Microorganisms have several benefits that make them more appealing for studying toxicity and mutations compared with different biological tests among the test organisms. Their advantages encompass their low expense, rapid development rates, and substantial population numbers. Moreover, several bacteria may be readily genetically altered, enabling the observation of their reactions to surrounding variations by producing specific signals [9]. These biosensors are utilized in healthcare, environmental monitoring, food safety, and biotechnology. Biosensors can be categorized according to their detection methodologies, such as electrochemical biosensors that assess current, voltage, or impedance, such as glucose monitors, optical biosensors (which employ fluorescence or surface plasmon resonance to identify biomolecular interactions), and piezoelectric biosensors (which measure mass alterations via frequency shifts). Bioanalytical methods enhance biosensors by utilizing chromatography, spectroscopy, and immunoassays to analyze biological samples with elevated sensitivity and specificity. Progress in nanotechnology and molecular biology consistently improves biosensor efficacy, rendering them vital instruments for swift and accurate detection across multiple domains. [11].

3. RECENT DEVELOPMENTS IN BIOSENSORS

Various electronic biomedical gadgets are available to assess human performance and conduct. The number of interconnected electronic devices worn worldwide is projected to increase from more than 300 million in 2016 to surpass 1 billion by 2022. Wireless omnipresent observing has emerged as an essential tool for medical and scientific fields in the past few years. In 1967, Updike and Hicks unveiled the initial biosensor. Biosensors primarily comprise an atomic identification factor. The cells, receptors in the body, organelles, antigens, connective tissues, microbes, and catalysts are widely utilized as MREs.

Artificial compounds, including MIPs (Chemically Written Polymers) and PNAs (Peptide Nucleic Acids), are employed as MREs. MREs have been categorized according to two types: affinity and catalytic bases. Electrochemical foundation MREs consist of plants or animals, enzymes, and others. Affinity-based recognition of biological elements, encompassing molecularly imprinted polymers, amino acid receptors in the skin, and antigens. The durability, temperature stability, and resistance to chemicals of biological sensors can be enhanced by using engineered and extracted enzymes and organisms. MIPs can be divided into two types: covalent bonds and non-covalent interactions. MIPs are employed as biological detectors developed for beta-estradiol, herbicides, and chloramphenicol [2, 12].

Micromachining, or micro-manufacturing techniques, integrates and reduces the size. In 1984, Karube et al. changed an enzymatic immunoassay biosensor, which employed reactions from the immune system. Biosensors that use electrodes are primarily constructed of polymers with conductivity. Plasma polymerized films (PPFs) are suitable for constructing biosensors [12].

4. SUBSTANCES FOR BIOSENSORS

Combining physiological detection components with organic, inorganic, or hybrid nanoparticles can facilitate the detection of chemical or biological substances, advancing innovative nano-biosensors. The rapid progress in nanotechnology has led to the creation of innovative nanoparticles and nanotechnology devices that hold promise for future healthcare and biological applications. Both of these methodologies can be employed to develop nano-biosensors utilizing nanoparticles. Nanotechnologies [13].

According to IUPAC, a biosensor is an instrument that utilizes specific biochemical processes caused by separate proteins, the body's immune cells, organelles that are present, or entire cells to detect organic substances, typically through electrical power, thermal energy, or optical signals. Biological sensing elements may comprise entire cells, antigens, enzymatic agents, and additional components. Sensitiveness and selectivity are both of the primary attributes of a biotech; sensitivity refers to the biosensor's detection capabilities, whereas selectivity varies depending on the type of species or detector utilized [14]. The detection method transfers sets from the biomolecular analyte to the nanotechnology. Nanomaterials are substances frequently deposited onto a promoting wafer's surface, creating a direct interface with the cellular detection element. Silicon nanowires, transmitting polymer carbon nanotubes, and graphene, and nanotubes made of carbon (CNT) are frequently employed in nanotechnology to enhance miniature biosensors. The efficacy of biological sensors can be improved by the implementation of technology known as integrated circuits. Materials based on thin insulating films, such as polysiloxanes, polyvinyl chloride, and polytetrafluoroethylene, are extensively utilized as prosthetic parts and implant systems encapsulations [15].

The devices are being placed to protect against the destructive effects of physiological fluids and serve as an electrical barrier. Ultrasonic elastic-guided beams might be employed to assess the incorporation of an intestinal transplant. Implants made from titanium are considered among the most advantageous tools for bone integration with bone tissue due to their resistance to infection. An innovative, non-invasive tomographic screening technique can effectively assess strain at Osseointegrated material and prostheses junctions. Carbon substances, including carbon nanofibers, nanotubes, graphene, and carbon black, can produce extremely adaptable and cost-efficient flexible biosensors [2, 16].

5. COMMON CATEGORIES OF BIOSENSORS

In resonating biosensors, a waveform transducer is integrated using an antibody or bio element. Its mass is altered upon binding the scientific material, or antibody, to the cell membrane. The change in weight next alters the resonating frequency of the sensor. Figure 3 shows a classification of biosensors, which are analytical instruments that combine biological elements with physicochemical detectors to measure diverse substances. Biosensors are primarily classified into two components: the bioelement and the sensor element. The bioelement comprises enzymes, antibodies, nucleic acids, tissues, microbial cells, and polysaccharides, each fulfilling a unique function in recognizing specific analytes. Enzymes catalyze biochemical reactions, such as antibodies binding to particular antigens, including nucleic acids, to identify genetic material; tissue samples detect biological changes; microbial cells respond to metabolic activities; and polysaccharides engage in molecular interactions. The sensor element is the transducing component that transforms the biological response into a quantifiable signal. Biosensors can also detect variations in the intensity and phase of electromagnetic radiation, facilitating optical sensing applications. Additional sensor elements encompass mass-based detection, which discerns alterations in mass resulting from molecular interactions, temperature measurement for thermal biosensors, and viscosity analysis for monitoring fluid properties. The bioelement and sensor element collaborate synergistically to deliver precise, swift, and sensitive detection of target substances, rendering biosensors essential instruments in medical diagnostics, environmental monitoring, food safety, and biotechnology. Biosensors utilize the specificity of biological components and the accuracy of sensor elements to provide real-time, dependable, and efficient detection, thereby enhancing scientific research and industrial applications. This classification emphasizes the diversity and functionality of biosensors, highlighting their importance in contemporary analytical methods [17].

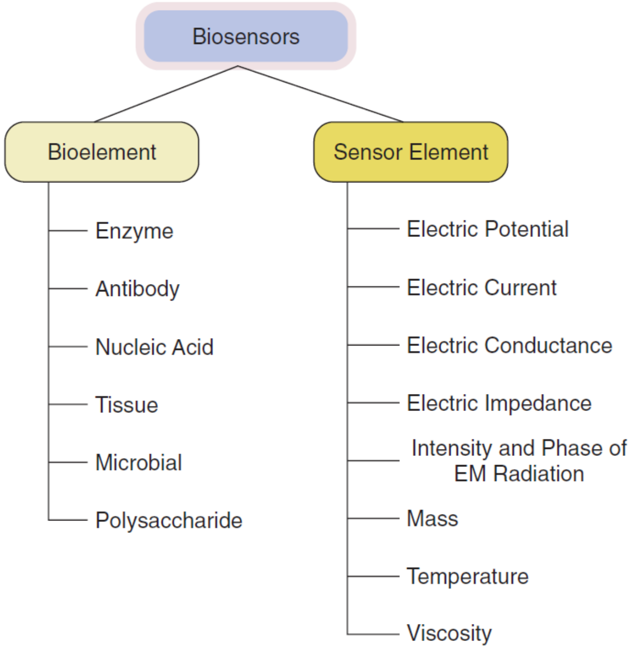

FIGURE 3. - Elements of biosensors [18]

This figure 3 illustrates two core components of biosensors: bio elements and sensor elements. Bio elements include biological molecules like enzymes, antibodies, nucleic acids, tissues, microbes, and polysaccharides, providing specificity for analyte detection. The sensor elements translate biological interactions into measurable signals through various physical properties such as electric potential, current, conductance, impedance, intensity, and phase of electromagnetic radiation, mass, temperature, and viscosity, enabling quantitative analysis and detection.

In optical biosensors, the output converted signal is quantified as photons. The biosensor may be fabricated via photonic diffract or electromagnetic radiation. A silicon wafer is coated with a protein using covalent bonds in an optically diffraction-based apparatus. The wafer undergoes UV radiation through a photomask, which deactivates antigens in the exposed areas. During the incubation period of the divided wafer chips in an analyte, antigen-antibody interactions transpire in the stimulated regions, forming a grating that scatters light. This grating produces a diffraction signal when illuminated by a light source, such as a laser. The generated signal can be noticed immediately or further amplified to improve the response before testing [17].

Thermal sensing biosensors exploit a key feature of many biological reactions—the release or absorption of heat, which leads to measurable changes in the temperature of the local environment. These biosensors are constructed by immobilizing enzyme particles onto temperature-sensitive components, typically thermistors. When the enzyme catalyzes a reaction with the target analyte, the resulting thermal exchange is directly proportional to both the molar enthalpy and the concentration of the interacting molecules. The temperature change is then quantified and correlated with the analyte level. Due to their exceptional sensitivity to minor thermal fluctuations, enzyme thermistors are particularly well-suited for detecting a wide range of chemical compounds and pathogenic microorganisms [19, 20].

The ion-sensitive field-effect transistor (ISFET) is typically fabricated by coating the sensor electrode with a polymeric film that exhibits selective permeability to specific analyte ions. As target ions diffuse through this polymer layer, they induce changes in the surface potential of the underlying field-effect transistor (FET). These potential shifts are then transduced into electrical signals, allowing for precise detection. A specialized variant, the enzyme field-effect transistor (ENFET), incorporates enzyme layers onto the ISFET structure to achieve greater specificity. ENFETs are particularly effective for pH sensing, as enzymatic reactions often produce or consume protons, resulting in measurable alterations in the local hydrogen ion concentration [19].

Because many biological samples lack inherent electroactivity, enzymes are frequently employed to catalyze reactions that generate electroactive or detectable products. Current is often the primary parameter measured in electrochemical biosensing, particularly in aerometric detection. Potentiometric biosensors, conversely, assess changes in the oxidation-reduction potential associated with specific electrochemical reactions. These sensors apply a controlled ramp voltage to an electrode immersed in a solution, initiating redox processes. As these reactions occur, the resulting voltage reflects the specific chemical reactivity and the analyte's identity, enabling selective and quantitative analysis of target species. This approach proves remarkably effective for monitoring ions, metabolites, and enzyme-substrate interactions in real time [21].

6. MEDICAL APPLICATIONS OF BIOSENSORS

Endocrine-disrupting chemicals (EDCs) can mimic or oppose the characteristics of estrogens and androgens. Endocrine-disrupting chemicals (EDCs) can interfere with the production and metabolism of several hormones and their receptors [8]. Consequently, regulatory authorities emphasize detecting and surveilling endocrine-disrupting chemicals (EDCs), given their widespread presence in industrial and household products. Common EDCs include polycyclic aromatic hydrocarbons (PAHs), dioxins, and polychlorinated biphenyls (PCBs). Human exposure to these substances primarily occurs through direct contact with contaminated surfaces, which may lead to severe reproductive health disorders such as birth defects, testicular and breast cancer, and reduced sperm quality. To address these risks, biosensors are increasingly employed in environmental and clinical settings to monitor EDCs. These biosensors are generally categorized into two types: the first measures the biological or hormonal effects induced by EDCs. In contrast, the second directly detects and quantifies specific EDC molecules or their groups in complex samples. Beyond environmental monitoring, biosensors demonstrate vast potential in medical diagnostics, patient monitoring, and drug development. In diabetes management, for example, glucose biosensors enable real-time tracking of blood sugar levels, thus optimizing therapeutic interventions. In infectious disease diagnostics, biosensors offer rapid, sensitive, and cost-efficient methods to detect bacterial and viral pathogens. These systems utilize specific biological recognition elements—such as antibodies, nucleic acids, or enzymes to identify target biomolecules like DNA, RNA, proteins, or metabolic products. Electrochemical biosensors register changes in current or potential generated by these interactions, while optical biosensors rely on fluorescence or surface plasmon resonance for signal transduction. Additionally, piezoelectric biosensors detect subtle changes in mass upon pathogen binding, making them particularly suitable for label-free detection in dynamic biological systems [22].

In recent years, advancements in nanotechnology and microfluidics have significantly improved biosensor sensitivity, enabling early disease detection with minimal sample volumes. Point-of-care biosensors allow real-time monitoring and diagnosis of infectious diseases such as COVID-19, tuberculosis, HIV, and malaria, reducing reliance on complex laboratory procedures [16]. The biosensor devices play a crucial role in outbreak control by providing rapid screening tools that help healthcare professionals implement timely interventions. The biosensors have further revolutionized infectious disease detection by offering highly specific and rapid viral and bacterial genetic material identification. Despite their numerous advantages, challenges such as biosensor stability, reproducibility, and potential interference from complex biological samples must be addressed to enhance reliability. Future research into nanomaterial-based biosensors, wearable diagnostics, and artificial intelligence-driven biosensing platforms will improve pathogen detection, leading to more effective disease management and public health strategies [22].

Biosensors enhance cancer diagnostics by identifying tumor markers in blood or tissue samples. They are also essential in wearable health monitoring devices, measuring biomarkers such as lactate, cholesterol, and oxygen levels for ongoing health evaluation. Progress in nanotechnology and microfluidics is augmenting biosensor sensitivity, specificity, and portability, rendering them essential instruments in contemporary healthcare [1, 22].

7. BIOSENSOR DESIGN

The necessity of overseeing vital procedures and variables across many sectors has resulted in the development of compact analytical instruments termed biosensors. The advent of such instruments has offered answers for many different uses, such as drug development, illness diagnostics, biomedicine, food quality, and tracking the environment, defense, and security, as illustrated. Biosensors are scientific instruments employed to detect the presence of a specific analyte in a sample. These profitable connected gadgets deliver subjective and semi-quantitative statistical information via a biological recognition element linked to a transmission component. The primary function of these analytical instruments is to swiftly deliver precise and dependable information on a specific analyte in real time [22]. Biosensor design strategically integrates a biological recognition element with a physical transducer to enable the detection of specific analytes and the conversion of biological interactions into measurable signals. The core components include a bioreceptor, such as enzymes, antibodies, nucleic acids (e.g., DNA or RNA), or whole cells, that selectively binds to the target analyte. Upon recognition, the interaction is transduced into a signal by a conversion element, which may be electrochemical, optical, piezoelectric, or thermal. This signal is subsequently amplified, processed, and interpreted by a signal processing unit, which presents the data in a readable form, such as digital output or colorimetric change. Recent advancements in nanomaterials, microfluidic platforms, and wireless communication technologies have significantly enhanced biosensor performance. These innovations facilitate the fabrication of miniaturized, portable, and highly sensitive biosensing devices. As a result, modern biosensors are increasingly applied in diverse sectors, including point-of-care medical diagnostics, real-time environmental monitoring, food safety assurance, and industrial process control. The continuous integration of cutting-edge technologies promises to improve biosensor functionality further, enabling faster, more accurate, and decentralized analytical capabilities [17]

As illustrated in Figure 4, a typical biosensor comprises three fundamental components: a biological recognition element, a transducer, and a signal processing unit. The biological recognition element interacts specifically with the target analyte to initiate a biochemical or physicochemical response. These sensing elements may include tissues, microbial cells, cellular receptors, organelles, antibodies, enzymes, or nucleic acids, each selected based on the desired specificity and application. Once the analyte binds to the biological component, the transducer converts the resulting interaction into a quantifiable signal, usually electrical in nature. The transducer serves as the critical link between biological activity and measurable output. Subsequently, the signal processing system amplifies and refines this signal, ensuring accuracy and minimizing noise. The final output is presented through user-friendly formats, such as digital displays, colorimetric changes, or printed readouts, thereby facilitating real-time analysis and interpretation in both laboratory and field settings [23, 24].

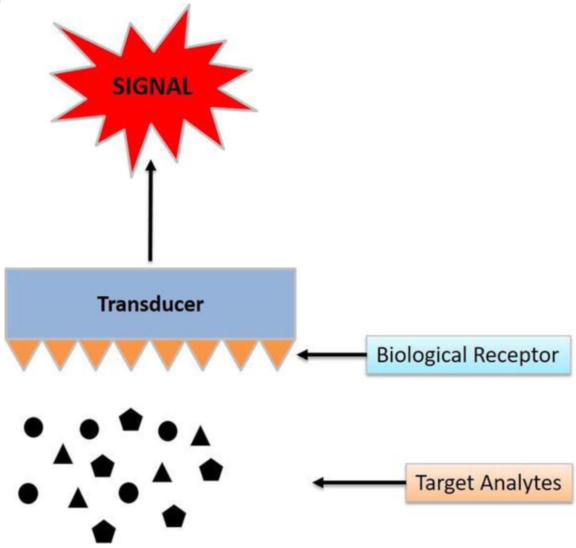

FIGURE 4. - Fundamental schematic of a biosensor. Image modified from Korotkaya [7]

Figure 4 depicts a simplified biosensor mechanism. Target analytes bind to biological receptors immobilized on a transducer surface. This binding event triggers the transducer to produce a detectable and measurable signal. The transducer thus acts as a critical intermediary, converting biochemical interactions between analytes and receptors into quantifiable signals, facilitating the sensitive and specific detection of various biological or chemical targets.

An excellent biosensor consists of two primary parts: an organism's receptor or sensor component and a transducer device. A signal synthesis unit, often equipped with a monitor or printing device, is generally utilized alongside a biosensor, as seen in Figure 5 [24]. A superior biosensor comprises two fundamental components: an organism's receptor or sensor element and a transducer device, which collaboratively function to identify and measure specific biological analytes. The receptor, typically comprised of biomolecules like enzymes, antibodies, nucleic acids, or entire cells, selectively engages with the target analyte, initiating a biochemical or physicochemical response [23]. Contemporary biosensors utilize sophisticated technologies, including microfluidics, nanomaterials, and wireless connectivity, to improve sensitivity, portability, and ease of use. The applications encompass medical diagnostics, including glucose monitoring, infectious disease detection, environmental monitoring, and food safety. Integrating biosensors with artificial intelligence and smartphone-based platforms facilitates remote healthcare monitoring, real-time analytics, and automated decision-making. Notwithstanding their myriad advantages, issues about stability, biocompatibility, and scalability must be resolved for extensive commercial implementation. Ongoing research in biosensor development seeks to improve precision, miniaturization, and multi-analyte detection capabilities, facilitating the advancement of next-generation diagnostic tools with enhanced efficiency and accuracy [24].

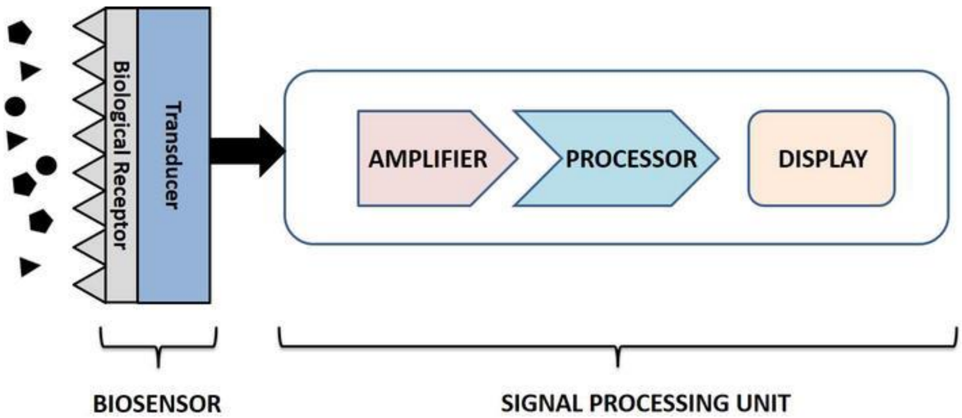

FIGURE 5. - Diagram of a biosensor illustrating the essential elements required for signal generation

Figure 5 represents a comprehensive biosensor system. Target analytes interact specifically with the biological receptors on the biosensor surface. The transducer transforms this interaction into an electrical signal. The generated signal is amplified to enhance its detectability, processed to interpret and quantify the data, and displayed as readable results. Thus, the signal processing unit ensures accurate, amplified, and user-friendly output from the biosensor interaction.

8. THE OPERATIONAL MECHANISM OF A BIOSENSOR

A biosensor comprises a biological recognition component integrated with a transducer and a signal processing unit, which combines biochemical interactions into measurable outputs. When a target analyte within a sample binds to the bioreceptor, such as an enzyme, antibody, or nucleic acid, it induces a specific physiological or biochemical change. This interaction influences the surrounding environment of the transducer, altering its physical or chemical properties, such as conductivity, optical absorbance, or surface potential. As a result, the transducer converts these changes into an electrical signal that correlates with the concentration or presence of the analyte. The signal is then processed, amplified, and displayed in a quantifiable format, enabling accurate molecular analysis. This mechanism allows biosensors to serve as highly effective tools for detecting biological activity in a wide range of analytical and diagnostic applications [25].

The output generated by a biosensor's transducer depends on the nature of the biorecognition event and may manifest as either electrical current or voltage. When the output is current, it is often converted into a corresponding voltage signal for easier handling. However, such signals are generally weak and susceptible to high-frequency noise, requiring further refinement. Therefore, signal conditioning steps, such as amplification, filtering, and noise reduction, are essential to extract meaningful data. The final processed signal must accurately represent the concentration or presence of the target analyte. A biosensor converts a biological interaction into a measurable output through well-defined stages. It comprises three essential modules: the biorecognition element, the transducer, and the signal processing system. The bioreceptor—commonly an enzyme, antibody, or nucleic acid, recognizes and binds to a specific target molecule. This molecular interaction triggers a physicochemical change, such as electron transfer, pH variation, or mass alteration. Depending on the sensor type, the transducer then converts this change into a measurable form, which may be electrical, optical, or thermal. Because of their high sensitivity, specificity, and rapid detection capabilities, biosensors are widely applied in clinical diagnostics, food quality control, and environmental monitoring [26].

9. CONCLUSION

In conclusion, biosensors have emerged as highly versatile analytical tools, integrating biological elements and transducers to detect and quantify diverse analytes across medical, environmental, and industrial sectors. Due to their inherent selectivity and sensitivity, biosensors significantly enhance diagnostic precision, particularly in glucose monitoring for diabetes management and early cancer detection through biomarker analysis. Moreover, their application in rapid pathogen identification has markedly improved infectious disease management, allowing timely interventions and reducing reliance on conventional laboratory methods. Additionally, biosensors' role in monitoring environmental pollutants, including endocrine-disrupting chemicals, underscores their utility in public health and ecological preservation. Recent technological advancements, such as incorporating nanomaterials, wireless systems, and artificial intelligence, further improve their sensitivity, portability, and real-time analysis capabilities. However, despite these advancements, persistent challenges such as device stability, reproducibility, and biocompatibility must be addressed comprehensively to facilitate broader adoption. If ongoing research addresses these issues effectively, biosensors will undoubtedly play a critical role in future diagnostics and monitoring systems. Therefore, the advancement of biosensor technology promises substantial benefits, including swift, reliable, and economical analysis, ultimately driving transformative changes in healthcare diagnostics, environmental monitoring, and industrial safety practices.

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CONFLICTS OF INTEREST

The authors disclose no conflicts of interest

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Biosensors applications in the medical field

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Biosensors applications in the medical field: A Review

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ABSTRACT: Biosensors are analytical instruments that combine biological recognition components with transducers to identify and measure analytes, vital in medical diagnostics, environmental surveillance, and industrial uses. This review examines advancements in biosensor technology, emphasizing their classification according to detection mechanisms, such as electrochemical, optical, piezoelectric, and thermal sensors. Biosensors are extensively utilized in the medical domain for glucose monitoring in diabetic individuals, early cancer detection via biomarker analysis, and swift identification of pathogens in infectious diseases. The biosensors are crucial in monitoring endocrine-disrupting chemicals (EDCs), and evaluating environmental pollutants. Recent advancements encompass the incorporation of wireless monitoring systems, artificial intelligence, and nanotechnology, markedly improving biosensor sensitivity, specificity, and real-time data processing capabilities. Miniaturized biosensors and wearable devices have transformed personalized medicine by facilitating continuous health monitoring. The innovations in enzyme-based biosensors, DNA biosensors, and immunosensors broadened their utility in disease diagnosis and pharmacological research. Issues such as stability, reproducibility, and biocompatibility continue to be pivotal domains of investigation. The future of biosensors is characterized by intelligent, multiplexed, and highly portable devices featuring enhanced real-time analytical capabilities. As biosensor technology advances, its significance in medicine and industry will increase, providing swift, economical, and precise detection instruments for various applications.

Keywords: Biosensors, DNA, Medical field, enzyme

1. INTRODUCTION

Biosensors represent analytical devices that convert biological interactions into measurable electrical signals. To ensure reliable performance, effective biosensors must demonstrate high precision, resistance to environmental fluctuations such as pH and temperature, and the capability for repeated use. The term “biosensor” was initially introduced by Cammann, with its definition later formalized by the International Union of Pure and Applied Chemistry (IUPAC) [1].

Developing biosensors involves a multidisciplinary approach that integrates principles from biology, chemical engineering, and materials science. Based on their functional mechanisms, biosensors are commonly divided into three main categories: biocatalytic sensors, which utilize enzymes; affinity-based sensors, which involve antibodies or nucleic acids; and microbial sensors, which rely on the activity of whole microorganisms [2].

The conceptual foundation for biosensors dates back to the 1960s through the pioneering work of Clark and Lyons. Since then, various types have emerged, including enzyme-based sensors, immunosensors, thermal sensors, and piezoelectric biosensors, each designed for specific applications [1, 3].

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Notably, Updike and Hicks introduced the first enzyme-based biosensor in 1967, employing immobilization techniques such as van der Waals adsorption, ionic interaction, and covalent attachment [4]. Commonly used enzymes include oxidoreductases, polyphenol oxidases, peroxidases, and amine oxidases.

Tissue-based biosensors, derived from plant or animal sources, typically function through interactions with substrates or inhibitors. For instance, Rechnitz developed an early tissue-based sensor to detect arginine concentrations using biological tissues. Additionally, organelle-based sensors utilize components like chloroplasts, mitochondria, and microsomes. While these systems offer high specificity, they often suffer from slow response times and limited sensitivity. The introduction of immunosensors marked a significant advancement, capitalizing on the high specificity of antibody-antigen interactions to detect toxins, pathogens, or other immune-related molecules within biological samples [5].

The fundamental principles of a biosensor's functionality are shown in Figure 1. Like an enzyme, a particular element identifies a certain unknown, and a sensing element converts the alteration into biological molecules into a signal of electricity. The aspect is individual to the chemical to which it responds [6]. It fails to identify additional analytes. The biosensors may be categorized based on the transmitting technology, comprising resonant biosensors, optically activated biosensors, thermal sensing biosensors, and electrochemical biosensors [7].

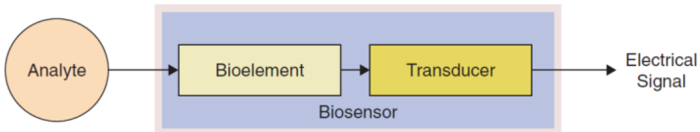

FIGURE 1. - A schematic representation of biosensors [8]

Figure 1 illustrates the fundamental working principle of a biosensor. Initially, the analyte interacts specifically with a bio element, such as an enzyme or antibody, facilitating selective detection. Subsequently, this biological interaction is converted by a transducer into an electrical signal. Thus, the biosensor effectively translates biochemical reactions into measurable electrical outputs, enabling precise quantification and analysis of biological substances in various practical and diagnostic applications.

The biosensors have diverse uses in healthcare, industrial, and military fields, as seen in Figure2 [9]. The biosensors possess substantial potential for industrialization across several applications, including biosensor-based equipment in beverages and food manufacturing, environmental monitoring, and sensitive medicinal analytic tools. Nonetheless, industry acceptance remains sluggish due to many obstacles to technology. For instance, the coexistence of microorganisms with semiconductor components presents a significant challenge regarding biosensor infection. DNA biosensors were created because a single-stranded nucleic acid molecule can detect and bond to its strand in a sample. Adding biosensor materials to a physical transducer creates thermal or calorimetric biosensors [8].

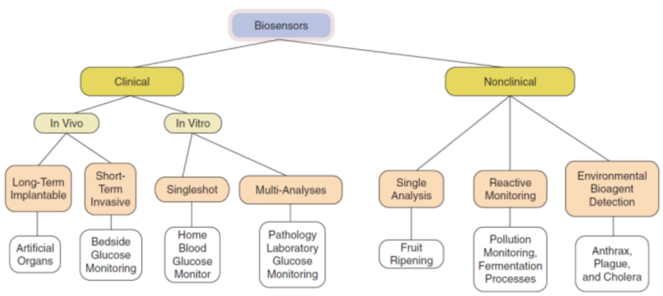

FIGURE 2. - Potential applications of biosensors

Figure 2 illustrates the primary classification of biosensors into clinical and nonclinical categories. Clinical biosensors are subdivided into in vivo systems, such as long-term implantable devices (e.g., artificial organs) and short-term invasive tools (e.g., bedside glucose monitors), and in vitro systems, which include single-use sensors for personal monitoring and multi-analyte devices utilized in clinical laboratories for comprehensive diagnostics, such as blood glucose assessments.

On the other hand, nonclinical biosensors are applied in a broader range of environmental and industrial settings. These include single-analyte applications, such as monitoring fruit ripening; dynamic or reactive systems for tracking fermentation processes and pollution levels; and biosensors dedicated to the detection of environmental bioagents, including pathogenic threats like Bacillus anthracis (anthrax), Yersinia pestis (plague), and Vibrio cholerae (cholera).

Optical biosensors consist of an electromagnetic source and additional electronic parts that generate a beam with specific characteristics, sending the resulting light toward a modifying agent, an altered sensing head, and a device that detects light [9].

The advent of green fluorescent protein (GFP), along with its evolved auto-fluorescent gene variants and genetically engineered fusion reporters, significantly advances the field of genetically encoded biosensors. These biosensors offer intuitive design, facile genetic manipulation, and efficient integration into living cells, enabling real-time monitoring of intracellular processes. Their modular nature facilitates customization for specific biological targets, making them invaluable tools in cellular imaging, functional genomics, and synthetic biology [10]. The single-chain Förster Resonance Energy Transfer (FRET) sensor is an illustrative example of genetically encoded biosensors. This system typically consists of a pair of auto-fluorescent proteins (AFPs) capable of transferring energy between each other when brought into proximity, thereby enabling the detection of molecular interactions or conformational changes. Multiple strategies are employed to optimize FRET signal dynamics, including adjustments in fluorescence intensity, emission ratios, or fluorescence lifetime measurements. In parallel, synthetic peptide- and protein-based biosensors are developed using advanced chemical synthesis and enzymatic labeling with synthetic fluorophores. Unlike genetically encoded FRET systems, these biosensors function independently of endogenous fluorescent proteins, providing increased design flexibility. Moreover, they offer enhanced signal-to-noise ratios and sensitivity by integrating features such as chemical quenchers and photoactivatable groups. These capabilities make them particularly valuable for monitoring dynamic biochemical activities and regulating molecular targets with high spatial and temporal resolution [7, 9].

2. BIOLOGICAL SENSORS AND BIOANALYTICAL METHODS

Biosensors can be distinctly distinguished from bioanalytical procedures and bioassays. Bioassays often encompass many processing stages, such as incorporating another reagent (e.g., enzymes or substrates). While most biosensors identify the individual analytes rather than a combination of several analytes, advancements in novel methods, such as array configurations. Generally, the application of biological sensors does not rival bioanalytical approaches. Biosensors are primarily engineered as the initial filter for collection screening through regulatory bodies. Consequently, the primary objective is to decrease the expenses associated with monitoring programs [2, 11].

While cytotoxicity experiments employing animals and larger organisms supply enhanced importance for humans compared to biosensors, they are accompanied by several restrictions in their application for cytotoxicity and mutation evaluations. These limits encompass time usage, expense, and spatial needs. Microorganisms have several benefits that make them more appealing for studying toxicity and mutations compared with different biological tests among the test organisms. Their advantages encompass their low expense, rapid development rates, and substantial population numbers. Moreover, several bacteria may be readily genetically altered, enabling the observation of their reactions to surrounding variations by producing specific signals [9]. These biosensors are utilized in healthcare, environmental monitoring, food safety, and biotechnology. Biosensors can be categorized according to their detection methodologies, such as electrochemical biosensors that assess current, voltage, or impedance, such as glucose monitors, optical biosensors (which employ fluorescence or surface plasmon resonance to identify biomolecular interactions), and piezoelectric biosensors (which measure mass alterations via frequency shifts). Bioanalytical methods enhance biosensors by utilizing chromatography, spectroscopy, and immunoassays to analyze biological samples with elevated sensitivity and specificity. Progress in nanotechnology and molecular biology consistently improves biosensor efficacy, rendering them vital instruments for swift and accurate detection across multiple domains. [11].

3. RECENT DEVELOPMENTS IN BIOSENSORS

Various electronic biomedical gadgets are available to assess human performance and conduct. The number of interconnected electronic devices worn worldwide is projected to increase from more than 300 million in 2016 to surpass 1 billion by 2022. Wireless omnipresent observing has emerged as an essential tool for medical and scientific fields in the past few years. In 1967, Updike and Hicks unveiled the initial biosensor. Biosensors primarily comprise an atomic identification factor. The cells, receptors in the body, organelles, antigens, connective tissues, microbes, and catalysts are widely utilized as MREs.

Artificial compounds, including MIPs (Chemically Written Polymers) and PNAs (Peptide Nucleic Acids), are employed as MREs. MREs have been categorized according to two types: affinity and catalytic bases. Electrochemical foundation MREs consist of plants or animals, enzymes, and others. Affinity-based recognition of biological elements, encompassing molecularly imprinted polymers, amino acid receptors in the skin, and antigens. The durability, temperature stability, and resistance to chemicals of biological sensors can be enhanced by using engineered and extracted enzymes and organisms. MIPs can be divided into two types: covalent bonds and non-covalent interactions. MIPs are employed as biological detectors developed for beta-estradiol, herbicides, and chloramphenicol [2, 12].

Micromachining, or micro-manufacturing techniques, integrates and reduces the size. In 1984, Karube et al. changed an enzymatic immunoassay biosensor, which employed reactions from the immune system. Biosensors that use electrodes are primarily constructed of polymers with conductivity. Plasma polymerized films (PPFs) are suitable for constructing biosensors [12].

4. SUBSTANCES FOR BIOSENSORS

Combining physiological detection components with organic, inorganic, or hybrid nanoparticles can facilitate the detection of chemical or biological substances, advancing innovative nano-biosensors. The rapid progress in nanotechnology has led to the creation of innovative nanoparticles and nanotechnology devices that hold promise for future healthcare and biological applications. Both of these methodologies can be employed to develop nano-biosensors utilizing nanoparticles. Nanotechnologies [13].

According to IUPAC, a biosensor is an instrument that utilizes specific biochemical processes caused by separate proteins, the body's immune cells, organelles that are present, or entire cells to detect organic substances, typically through electrical power, thermal energy, or optical signals. Biological sensing elements may comprise entire cells, antigens, enzymatic agents, and additional components. Sensitiveness and selectivity are both of the primary attributes of a biotech; sensitivity refers to the biosensor's detection capabilities, whereas selectivity varies depending on the type of species or detector utilized [14]. The detection method transfers sets from the biomolecular analyte to the nanotechnology. Nanomaterials are substances frequently deposited onto a promoting wafer's surface, creating a direct interface with the cellular detection element. Silicon nanowires, transmitting polymer carbon nanotubes, and graphene, and nanotubes made of carbon (CNT) are frequently employed in nanotechnology to enhance miniature biosensors. The efficacy of biological sensors can be improved by the implementation of technology known as integrated circuits. Materials based on thin insulating films, such as polysiloxanes, polyvinyl chloride, and polytetrafluoroethylene, are extensively utilized as prosthetic parts and implant systems encapsulations [15].

The devices are being placed to protect against the destructive effects of physiological fluids and serve as an electrical barrier. Ultrasonic elastic-guided beams might be employed to assess the incorporation of an intestinal transplant. Implants made from titanium are considered among the most advantageous tools for bone integration with bone tissue due to their resistance to infection. An innovative, non-invasive tomographic screening technique can effectively assess strain at Osseointegrated material and prostheses junctions. Carbon substances, including carbon nanofibers, nanotubes, graphene, and carbon black, can produce extremely adaptable and cost-efficient flexible biosensors [2, 16].

5. COMMON CATEGORIES OF BIOSENSORS

In resonating biosensors, a waveform transducer is integrated using an antibody or bio element. Its mass is altered upon binding the scientific material, or antibody, to the cell membrane. The change in weight next alters the resonating frequency of the sensor. Figure 3 shows a classification of biosensors, which are analytical instruments that combine biological elements with physicochemical detectors to measure diverse substances. Biosensors are primarily classified into two components: the bioelement and the sensor element. The bioelement comprises enzymes, antibodies, nucleic acids, tissues, microbial cells, and polysaccharides, each fulfilling a unique function in recognizing specific analytes. Enzymes catalyze biochemical reactions, such as antibodies binding to particular antigens, including nucleic acids, to identify genetic material; tissue samples detect biological changes; microbial cells respond to metabolic activities; and polysaccharides engage in molecular interactions. The sensor element is the transducing component that transforms the biological response into a quantifiable signal. Biosensors can also detect variations in the intensity and phase of electromagnetic radiation, facilitating optical sensing applications. Additional sensor elements encompass mass-based detection, which discerns alterations in mass resulting from molecular interactions, temperature measurement for thermal biosensors, and viscosity analysis for monitoring fluid properties. The bioelement and sensor element collaborate synergistically to deliver precise, swift, and sensitive detection of target substances, rendering biosensors essential instruments in medical diagnostics, environmental monitoring, food safety, and biotechnology. Biosensors utilize the specificity of biological components and the accuracy of sensor elements to provide real-time, dependable, and efficient detection, thereby enhancing scientific research and industrial applications. This classification emphasizes the diversity and functionality of biosensors, highlighting their importance in contemporary analytical methods [17].

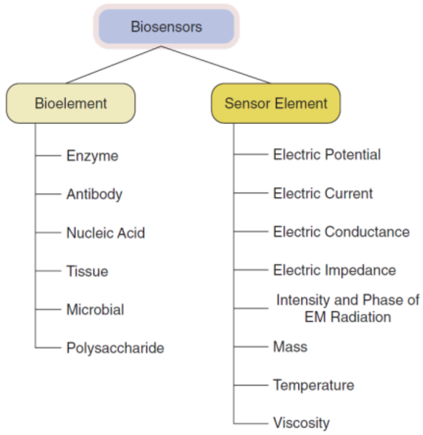

FIGURE 3. - Elements of biosensors [18]

This figure 3 illustrates two core components of biosensors: bio elements and sensor elements. Bio elements include biological molecules like enzymes, antibodies, nucleic acids, tissues, microbes, and polysaccharides, providing specificity for analyte detection. The sensor elements translate biological interactions into measurable signals through various physical properties such as electric potential, current, conductance, impedance, intensity, and phase of electromagnetic radiation, mass, temperature, and viscosity, enabling quantitative analysis and detection.

In optical biosensors, the output converted signal is quantified as photons. The biosensor may be fabricated via photonic diffract or electromagnetic radiation. A silicon wafer is coated with a protein using covalent bonds in an optically diffraction-based apparatus. The wafer undergoes UV radiation through a photomask, which deactivates antigens in the exposed areas. During the incubation period of the divided wafer chips in an analyte, antigen-antibody interactions transpire in the stimulated regions, forming a grating that scatters light. This grating produces a diffraction signal when illuminated by a light source, such as a laser. The generated signal can be noticed immediately or further amplified to improve the response before testing [17].

Thermal sensing biosensors exploit a key feature of many biological reactions—the release or absorption of heat, which leads to measurable changes in the temperature of the local environment. These biosensors are constructed by immobilizing enzyme particles onto temperature-sensitive components, typically thermistors. When the enzyme catalyzes a reaction with the target analyte, the resulting thermal exchange is directly proportional to both the molar enthalpy and the concentration of the interacting molecules. The temperature change is then quantified and correlated with the analyte level. Due to their exceptional sensitivity to minor thermal fluctuations, enzyme thermistors are particularly well-suited for detecting a wide range of chemical compounds and pathogenic microorganisms [19, 20].

The ion-sensitive field-effect transistor (ISFET) is typically fabricated by coating the sensor electrode with a polymeric film that exhibits selective permeability to specific analyte ions. As target ions diffuse through this polymer layer, they induce changes in the surface potential of the underlying field-effect transistor (FET). These potential shifts are then transduced into electrical signals, allowing for precise detection. A specialized variant, the enzyme field-effect transistor (ENFET), incorporates enzyme layers onto the ISFET structure to achieve greater specificity. ENFETs are particularly effective for pH sensing, as enzymatic reactions often produce or consume protons, resulting in measurable alterations in the local hydrogen ion concentration [19].

Because many biological samples lack inherent electroactivity, enzymes are frequently employed to catalyze reactions that generate electroactive or detectable products. Current is often the primary parameter measured in electrochemical biosensing, particularly in aerometric detection. Potentiometric biosensors, conversely, assess changes in the oxidation-reduction potential associated with specific electrochemical reactions. These sensors apply a controlled ramp voltage to an electrode immersed in a solution, initiating redox processes. As these reactions occur, the resulting voltage reflects the specific chemical reactivity and the analyte's identity, enabling selective and quantitative analysis of target species. This approach proves remarkably effective for monitoring ions, metabolites, and enzyme-substrate interactions in real time [21].

6. MEDICAL APPLICATIONS OF BIOSENSORS

Endocrine-disrupting chemicals (EDCs) can mimic or oppose the characteristics of estrogens and androgens. Endocrine-disrupting chemicals (EDCs) can interfere with the production and metabolism of several hormones and their receptors [8]. Consequently, regulatory authorities emphasize detecting and surveilling endocrine-disrupting chemicals (EDCs), given their widespread presence in industrial and household products. Common EDCs include polycyclic aromatic hydrocarbons (PAHs), dioxins, and polychlorinated biphenyls (PCBs). Human exposure to these substances primarily occurs through direct contact with contaminated surfaces, which may lead to severe reproductive health disorders such as birth defects, testicular and breast cancer, and reduced sperm quality. To address these risks, biosensors are increasingly employed in environmental and clinical settings to monitor EDCs. These biosensors are generally categorized into two types: the first measures the biological or hormonal effects induced by EDCs. In contrast, the second directly detects and quantifies specific EDC molecules or their groups in complex samples. Beyond environmental monitoring, biosensors demonstrate vast potential in medical diagnostics, patient monitoring, and drug development. In diabetes management, for example, glucose biosensors enable real-time tracking of blood sugar levels, thus optimizing therapeutic interventions. In infectious disease diagnostics, biosensors offer rapid, sensitive, and cost-efficient methods to detect bacterial and viral pathogens. These systems utilize specific biological recognition elements—such as antibodies, nucleic acids, or enzymes to identify target biomolecules like DNA, RNA, proteins, or metabolic products. Electrochemical biosensors register changes in current or potential generated by these interactions, while optical biosensors rely on fluorescence or surface plasmon resonance for signal transduction. Additionally, piezoelectric biosensors detect subtle changes in mass upon pathogen binding, making them particularly suitable for label-free detection in dynamic biological systems [22].

In recent years, advancements in nanotechnology and microfluidics have significantly improved biosensor sensitivity, enabling early disease detection with minimal sample volumes. Point-of-care biosensors allow real-time monitoring and diagnosis of infectious diseases such as COVID-19, tuberculosis, HIV, and malaria, reducing reliance on complex laboratory procedures [16]. The biosensor devices play a crucial role in outbreak control by providing rapid screening tools that help healthcare professionals implement timely interventions. The biosensors have further revolutionized infectious disease detection by offering highly specific and rapid viral and bacterial genetic material identification. Despite their numerous advantages, challenges such as biosensor stability, reproducibility, and potential interference from complex biological samples must be addressed to enhance reliability. Future research into nanomaterial-based biosensors, wearable diagnostics, and artificial intelligence-driven biosensing platforms will improve pathogen detection, leading to more effective disease management and public health strategies [22].

Biosensors enhance cancer diagnostics by identifying tumor markers in blood or tissue samples. They are also essential in wearable health monitoring devices, measuring biomarkers such as lactate, cholesterol, and oxygen levels for ongoing health evaluation. Progress in nanotechnology and microfluidics is augmenting biosensor sensitivity, specificity, and portability, rendering them essential instruments in contemporary healthcare [1, 22].

7. BIOSENSOR DESIGN

The necessity of overseeing vital procedures and variables across many sectors has resulted in the development of compact analytical instruments termed biosensors. The advent of such instruments has offered answers for many different uses, such as drug development, illness diagnostics, biomedicine, food quality, and tracking the environment, defense, and security, as illustrated. Biosensors are scientific instruments employed to detect the presence of a specific analyte in a sample. These profitable connected gadgets deliver subjective and semi-quantitative statistical information via a biological recognition element linked to a transmission component. The primary function of these analytical instruments is to swiftly deliver precise and dependable information on a specific analyte in real time [22]. Biosensor design strategically integrates a biological recognition element with a physical transducer to enable the detection of specific analytes and the conversion of biological interactions into measurable signals. The core components include a bioreceptor, such as enzymes, antibodies, nucleic acids (e.g., DNA or RNA), or whole cells, that selectively binds to the target analyte. Upon recognition, the interaction is transduced into a signal by a conversion element, which may be electrochemical, optical, piezoelectric, or thermal. This signal is subsequently amplified, processed, and interpreted by a signal processing unit, which presents the data in a readable form, such as digital output or colorimetric change. Recent advancements in nanomaterials, microfluidic platforms, and wireless communication technologies have significantly enhanced biosensor performance. These innovations facilitate the fabrication of miniaturized, portable, and highly sensitive biosensing devices. As a result, modern biosensors are increasingly applied in diverse sectors, including point-of-care medical diagnostics, real-time environmental monitoring, food safety assurance, and industrial process control. The continuous integration of cutting-edge technologies promises to improve biosensor functionality further, enabling faster, more accurate, and decentralized analytical capabilities [17]

As illustrated in Figure 4, a typical biosensor comprises three fundamental components: a biological recognition element, a transducer, and a signal processing unit. The biological recognition element interacts specifically with the target analyte to initiate a biochemical or physicochemical response. These sensing elements may include tissues, microbial cells, cellular receptors, organelles, antibodies, enzymes, or nucleic acids, each selected based on the desired specificity and application. Once the analyte binds to the biological component, the transducer converts the resulting interaction into a quantifiable signal, usually electrical in nature. The transducer serves as the critical link between biological activity and measurable output. Subsequently, the signal processing system amplifies and refines this signal, ensuring accuracy and minimizing noise. The final output is presented through user-friendly formats, such as digital displays, colorimetric changes, or printed readouts, thereby facilitating real-time analysis and interpretation in both laboratory and field settings [23, 24].

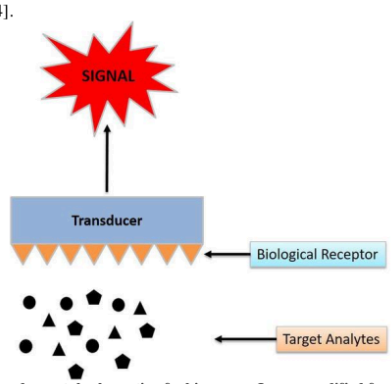

FIGURE 4. - Fundamental schematic of a biosensor. Image modified from Korotkaya [7]

Figure 4 depicts a simplified biosensor mechanism. Target analytes bind to biological receptors immobilized on a transducer surface. This binding event triggers the transducer to produce a detectable and measurable signal. The transducer thus acts as a critical intermediary, converting biochemical interactions between analytes and receptors into quantifiable signals, facilitating the sensitive and specific detection of various biological or chemical targets.

An excellent biosensor consists of two primary parts: an organism's receptor or sensor component and a transducer device. A signal synthesis unit, often equipped with a monitor or printing device, is generally utilized alongside a biosensor, as seen in Figure 5 [24]. A superior biosensor comprises two fundamental components: an organism's receptor or sensor element and a transducer device, which collaboratively function to identify and measure specific biological analytes. The receptor, typically comprised of biomolecules like enzymes, antibodies, nucleic acids, or entire cells, selectively engages with the target analyte, initiating a biochemical or physicochemical response [23]. Contemporary biosensors utilize sophisticated technologies, including microfluidics, nanomaterials, and wireless connectivity, to improve sensitivity, portability, and ease of use. The applications encompass medical diagnostics, including glucose monitoring, infectious disease detection, environmental monitoring, and food safety. Integrating biosensors with artificial intelligence and smartphone-based platforms facilitates remote healthcare monitoring, real-time analytics, and automated decision-making. Notwithstanding their myriad advantages, issues about stability, biocompatibility, and scalability must be resolved for extensive commercial implementation. Ongoing research in biosensor development seeks to improve precision, miniaturization, and multi-analyte detection capabilities, facilitating the advancement of next-generation diagnostic tools with enhanced efficiency and accuracy [24].

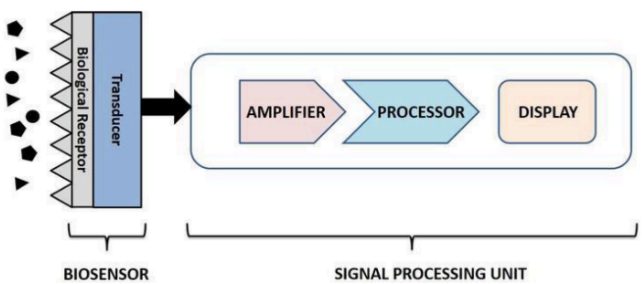

FIGURE 5. - Diagram of a biosensor illustrating the essential elements required for signal generation

Figure 5 represents a comprehensive biosensor system. Target analytes interact specifically with the biological receptors on the biosensor surface. The transducer transforms this interaction into an electrical signal. The generated signal is amplified to enhance its detectability, processed to interpret and quantify the data, and displayed as readable results. Thus, the signal processing unit ensures accurate, amplified, and user-friendly output from the biosensor interaction.

8. THE OPERATIONAL MECHANISM OF A BIOSENSOR

A biosensor comprises a biological recognition component integrated with a transducer and a signal processing unit, which combines biochemical interactions into measurable outputs. When a target analyte within a sample binds to the bioreceptor, such as an enzyme, antibody, or nucleic acid, it induces a specific physiological or biochemical change. This interaction influences the surrounding environment of the transducer, altering its physical or chemical properties, such as conductivity, optical absorbance, or surface potential. As a result, the transducer converts these changes into an electrical signal that correlates with the concentration or presence of the analyte. The signal is then processed, amplified, and displayed in a quantifiable format, enabling accurate molecular analysis. This mechanism allows biosensors to serve as highly effective tools for detecting biological activity in a wide range of analytical and diagnostic applications [25].

The output generated by a biosensor's transducer depends on the nature of the biorecognition event and may manifest as either electrical current or voltage. When the output is current, it is often converted into a corresponding voltage signal for easier handling. However, such signals are generally weak and susceptible to high-frequency noise, requiring further refinement. Therefore, signal conditioning steps, such as amplification, filtering, and noise reduction, are essential to extract meaningful data. The final processed signal must accurately represent the concentration or presence of the target analyte. A biosensor converts a biological interaction into a measurable output through well-defined stages. It comprises three essential modules: the biorecognition element, the transducer, and the signal processing system. The bioreceptor—commonly an enzyme, antibody, or nucleic acid, recognizes and binds to a specific target molecule. This molecular interaction triggers a physicochemical change, such as electron transfer, pH variation, or mass alteration. Depending on the sensor type, the transducer then converts this change into a measurable form, which may be electrical, optical, or thermal. Because of their high sensitivity, specificity, and rapid detection capabilities, biosensors are widely applied in clinical diagnostics, food quality control, and environmental monitoring [26].

9. CONCLUSION

In conclusion, biosensors have emerged as highly versatile analytical tools, integrating biological elements and transducers to detect and quantify diverse analytes across medical, environmental, and industrial sectors. Due to their inherent selectivity and sensitivity, biosensors significantly enhance diagnostic precision, particularly in glucose monitoring for diabetes management and early cancer detection through biomarker analysis. Moreover, their application in rapid pathogen identification has markedly improved infectious disease management, allowing timely interventions and reducing reliance on conventional laboratory methods. Additionally, biosensors' role in monitoring environmental pollutants, including endocrine-disrupting chemicals, underscores their utility in public health and ecological preservation. Recent technological advancements, such as incorporating nanomaterials, wireless systems, and artificial intelligence, further improve their sensitivity, portability, and real-time analysis capabilities. However, despite these advancements, persistent challenges such as device stability, reproducibility, and biocompatibility must be addressed comprehensively to facilitate broader adoption. If ongoing research addresses these issues effectively, biosensors will undoubtedly play a critical role in future diagnostics and monitoring systems. Therefore, the advancement of biosensor technology promises substantial benefits, including swift, reliable, and economical analysis, ultimately driving transformative changes in healthcare diagnostics, environmental monitoring, and industrial safety practices.

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CONFLICTS OF INTEREST

The authors disclose no conflicts of interest

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