



## RESEARCH ARTICLE

# Biosensors and Their Applications in Various Fields

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## ABSTRACT

Biosensors are analytical devices that integrate biological recognition elements with transducers to detect specific analytes, offering high sensitivity, selectivity, and real-time monitoring capabilities. Biological sensors are playing a major and crucial role nowadays in many fields, whether it be medical diagnosis or monitoring the environment, drug discovery, forensics, and many more. The use of biosensors has made immense progress in the field of technology. In healthcare, biosensors are pivotal in detecting biomarkers for diseases, monitoring blood glucose, and managing chronic conditions. Food industries leverage biosensors for freshness evaluation and contamination detection, while biotechnology utilizes them for monitoring fermentation and cell culture processes. The continuous advancements in nanotechnology and microfabrication are further enhancing biosensor sensitivity and portability, driving their future potential in personalized medicine and point-of-care (PoC) diagnostics. Biosensors are also made from biological components and have become a game-changer. This review paper explores biosensors, their components, and their use in various fields.

## 1 | Introduction

The biosensor word was created by merging the terms bio, which refers to biology or living things, and sensor, which refers to a system or device that detects and responds to inputs [1]. By generating signals that are proportional to the analyte concentration in the reaction, a biosensor is a device that detects biological or chemical reactions [2]. Analytical tools called biosensors translate a biological reaction into an electrical signal. Fundamentally, biosensors need to be reusable, extremely specific, and unaffected by physical factors like pH and temperature [3]. Cammann is recognized for coining the term biosensor [4]. “A chemical sensing device in which a biologically derived recognition is coupled to a transducer, to allow the quantitative development of some complex biochemical parameter, is a biosensor.”

Biosensors can detect and quantify even low quantities of some diseases, harmful chemicals, and pH levels. They are available in a variety of sizes and shapes.

Numerous biosensors have been documented as end-user and time-saving analytical techniques for the detection of multiple analytes within the past 60 years [5]. By trapping glucose oxidase in a dialysis membrane over a Clark-type oxygen electrode, Professor Leland C. Clark reported the first example of an enzyme electrochemical biosensor in 1962 [6]. Leland Clark is also regarded as the father of biosensors. Additionally, Guilbault and Montalvo described using potentiometry to determine the urea concentration using glass electrodes and urease [7]. In addition to these initial instances, electrochemical transducers have been used in conjunction with deoxyribonucleic acid (DNA),

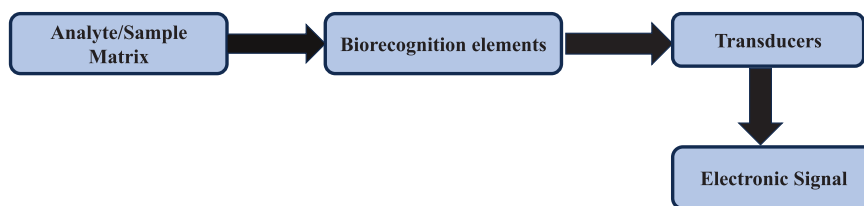


FIGURE 1 | Flowchart depicting the components of a typical biosensor.

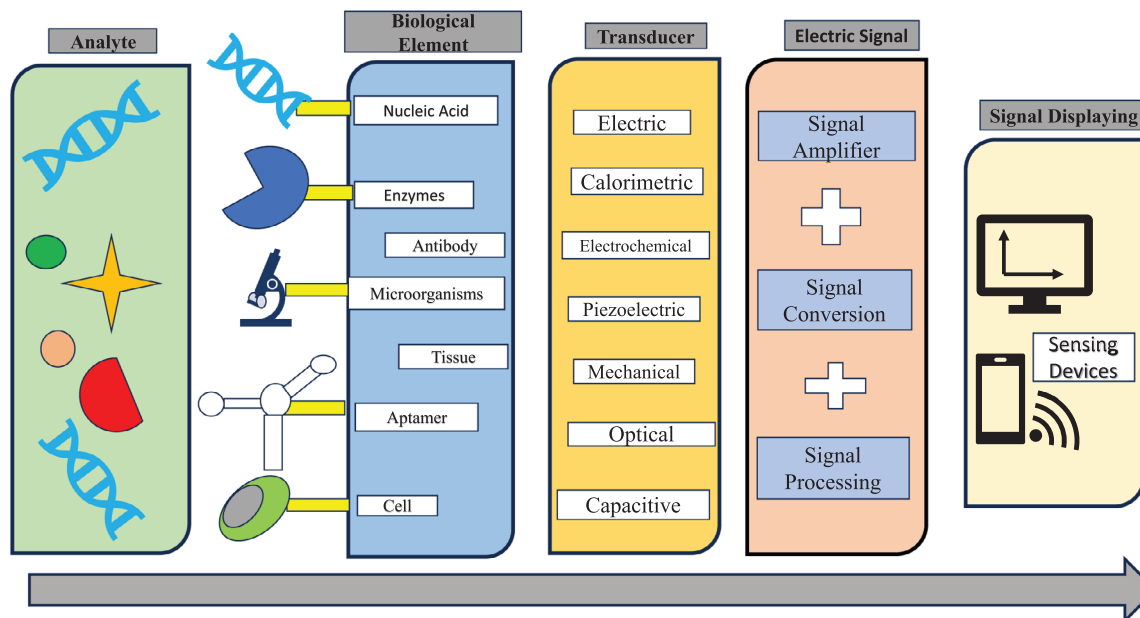


FIGURE 2 | Main components of biosensors.

enzymes, and antibodies as biochemical recognition components. Research spanning multiple disciplines in chemistry, biology, and engineering is necessary for the fabrication of biosensors, their materials, transducing devices, and immobilization techniques [8]. Presently, they make up the largest class of biosensors used in environmental, clinical, and food sensing [5]. These biosensors consist of certain components that have been explained with the help of a flowchart, and a pictorial representation of the same has been shown in Figures 1 and 2, respectively.

## 2 | Literature Review

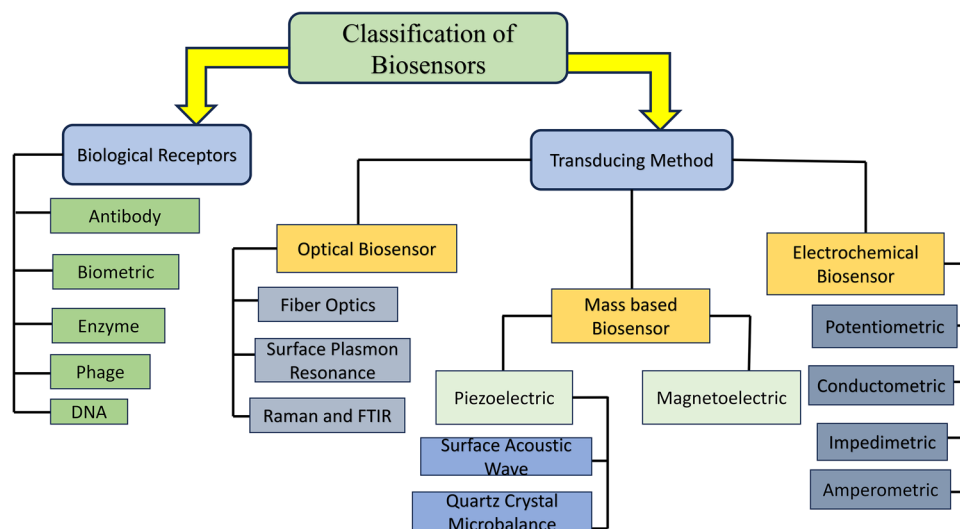
### 2.1 | Classification of Biosensors

Biosensors can be categorized based on their transduction or biological element. Enzymes, antibodies, microorganisms, biological tissue, and organelles are examples of biological elements. The kind of physicochemical alteration brought on by the sensing event determines the transduction technique. Transducer element-based biosensors are primarily mass-based, electrochemical, and optical [9]. This grouping or classification of the biosensors has been explained with a flowchart, as illustrated in Figure 3.

Optical biosensors have demonstrated valuable performance in identifying biological systems and driving important advance-

ments in environmental monitoring, drug development, clinical diagnostics, and food industry management [10]. Optical biosensors represent the most common type of biosensor [8, 11]. A light source and several optical components work together to create a light beam with particular properties that are directed at a modulating agent, a modified sensing head, and a photodetector in optical biosensors [12]. Various Optical biosensors were invented based on surface Plasmon resonance, spectroscopy, and evanescent waves.

Analytical tools that transform biochemical processes, such as enzyme-substrate reactions and antigen-antibody interactions, into electrical signals are known as electrochemical biosensors [13, 14]. Electrochemical Biosensors include Potentiometric, Conductometric, Impedimetric, and Amperometric devices known as mass-based biosensors that use changes in mass to identify biological interactions. The underlying idea behind these sensors is that biological materials, such as proteins, DNA, or microorganisms, change the mass of a surface when they attach to it. High-sensitivity measurements of this mass change allow for real-time biological event monitoring. It includes sensors like Magnetolectric and Piezoelectric. DNA biosensors are analytical tools that employ molecular recognition to identify and quantify biological entities, such as proteins, pathogens, or nucleic acids, using DNA or compounds related to DNA [15]. The economic potential of biotechnology has recently accelerated two decades of biosensor research [16].



**FIGURE 3** | Flowchart illustrating several biosensor types categorized by transducer and bio-recognition elements.

## 2.2 | Trends and Development of Different Biosensors

“Give a man a biosensor, and you enable him to unlock a world of cost-effective solutions for research, diagnosis, and personalized healthcare” [1]. Biosensors have been heralded as revolutionary advances in healthcare and research [17]. Biosensors can potentially improve the industrial sector’s sustainability, reduce waste, and boost production [17]. These biosensors are widely employed in many fields, improving the current form and increasing their specificity for many purposes [18]. Diagnosing diseases has several uses and is an essential part of providing quality healthcare. By directing epidemiological surveillance, resource allocation, and preventative measures, diagnostics support public health in ways that go beyond individual health. Additionally, it has a big influence on medical research, assisting in the development of new treatments [19, 20]. Disease diagnosis has been transformed by microbial biotechnology. Microbial biotechnology may aid in disease diagnostics by creating biosensors. Microbial biosensors are useful instruments for early and effective disease detection because of their versatility and real-time monitoring capabilities [20–22].

With respect to its high surface area, mechanical robustness, and biocompatibility, bacterial cellulose has possibilities as a biosensor material in medical applications. The fermentation of carbohydrates by certain bacteria, mainly *Gluconacetobacter*, yields [23]. Because of its hydrophilic properties, bacterial cellulose facilitates the adsorption of biomolecules onto its surface. It has drawn interest in a number of biomedical applications [23, 24].

As it is a known fact that Cancer is a major cause of death all over the world, but if detected in early stages, then it can be cured to some extent. So, with point-of-care technologies like lab-on-a-chips and wearable sensors, biosensors have become a viable way to enhance early cancer detection [25].

Nanomaterial-based biosensors have emerged as a promising technology for detecting biological molecules, like biomarkers,

proteins, and nucleic acids, with high sensitivity and selectivity. The use of nanoparticle-based detection techniques to develop rapid and effective detection assays has increased recently. Each and every one of these systems uses the unique properties of NPs to detect disease [26].

It has become difficult to determine the presence or concentration of biological analytes due to the integration of engineering and medical research, as well as the use of artificial intelligence to provide more precise results, particularly for preventive health care. The basic building blocks of such a system require recognition of an analyte, producing a signal that must be passed through a signal conditioning unit, and, finally, a detector that recognizes the specific analyte [27]. Biosensors based on microalgae have shown great potential for detecting toxins, pollutants, and other analytes in various applications. Recent advances in genetics and biotechnology have made it possible to apply synthetic biology techniques to new classes of microbial hosts, such as photosynthetic microalgae, which present special opportunities. Optical biosensors, due to their speedy, highly sensitive, and selective readings, have given biotechnology, environmental investigations, disease diagnostics, and medical applications a competitive edge [28]. Biosensors for sensitive and specific detection of foodborne and waterborne pathogens are particularly valued for their portability, usability, relatively low cost, and real-time or near-real-time response [29]. The unique properties of aptamers and gold nanoparticles have made aptamer-conjugated gold nanomaterials a potent platform for biosensing applications. Both aptamer and gold nanoparticle properties, such as strong binding affinity, high biocompatibility, improved target selectivity, and extended circulation half-life, are synergistically present in aptamer-conjugated gold nanoparticle complexes [30].

Cost-effective biosensors are being used by medical organizations and research scientists to test water and food toxins, regulate human biological processes, make accurate health diagnoses, and more. Researchers and medical practitioners need safe and cheaper means of performing their research, ensuring public safety, and delivering customized health options to patients. One

such solution can be easily carried out by using biosensors [31]. A key component in the successful and efficient treatment of cancer is early diagnosis. Conventional cancer screening diagnostic techniques are expensive, time-consuming, and impractical for frequent examinations. Nonetheless, one of the most promising approaches for early detection, tracking the course of the disease, and subsequent cancer treatment is a biomarker-based cancer diagnosis [32]. Biosensors use a variety of biorecognition components, including antibodies, enzymes, DNA, ribonucleic acid (RNA), cancer cells, nucleic acid probes, or other particular biomolecules that are immobilized on a transducer surface, to identify cancer biomarkers [32]. Biosensors have emerged as cardiac healthcare's future [33]. In the future, these biosensors may also be utilized as a substitute for the detection of the coronavirus and other viruses. Given that they provide quick, highly sensitive, and selective viral illness detection, they might be a good substitute [34].

Immobilized enzyme-based electrochemical biosensors are among the most widely used and economically successful types of biosensors. They are used in a wide range of fields, including household appliances, biotechnology, agriculture, food industry, clinical diagnosis, and environmental monitoring [33, 35–38].

Due to numerous benefits over current diagnostic technologies, including high accuracy, non-invasive nature, cost-effectiveness, easily interpretable results, and multiplexing capability, biosensor-based diagnostic technology has recently attracted a lot of attention for the early detection of various cancer types and other non-oncological disorders [39].

For almost fifty years, organophosphorus pesticides have been used extensively as domestic and agricultural pest control agents. These chemicals continue to exist in our water supplies, fruits, vegetables, and processed foods as harmful substances for human health and the environment. Therefore, it is imperative that these dangerous Organophosphorus pesticides be easily detected with great sensitivity and selectivity. These criteria are met by biosensing technology, which has been widely used for detection [40].

The most significant sterol produced by the majority of human cells, primarily in the liver, is cholesterol. It serves as a precursor for the manufacture of bile acids, vitamin D, and steroid hormones, and is an essential component of cell membranes. Mostly found in plasma as low-density lipoproteins, cholesterol is predominantly removed from tissues to the liver by high-density lipoproteins, which are then excreted in the bile [41].

The invention of biosensing instruments gained a lot of attention due to their real-time response, simplicity, low cost, great sensitivity, selectivity, and reliability. Finding areas of water contamination that require treatment depends on monitoring contaminants in wastewater effluents. Multiple hazardous components in wastewater are difficult to trace using conventional detection methods because they vary over time and from different sources. The creation of biosensing devices has garnered a lot of interest lately due to their high sensitivity, selectivity, dependability, simplicity, affordability, and real-time response [41]. Miniaturized systems known as biosensors also make it possible to create portable sensors that can continuously monitor

wastewater. The primary issues of detecting small molecules at ultralow concentrations and creating compact devices for point-of-care analysis are addressed by plasmonic biosensing, which has been employed for quick, real-time, and label-free probing of biologically relevant analytes [41].

Significant improvements in analytics are being made possible by biosensors, which in turn are enabling and being enabled by advancements in synthetic biology.

Recent innovations in developing biosensors, which are basically sensitive and specific, have opened new opportunities for DNA biosensors. DNA biosensors, based on nucleic acid recognition methods, are being developed toward the assay of rapid, simple, and economical testing of genetic and infectious diseases [41]. Since environmental pollution and human health/socioeconomic development are closely related, environmental monitoring has been a top priority on both a European and worldwide level. Biosensors have been used extensively in this field as quick, inexpensive, in situ, and real-time analytical methods [42].

Biosensor's performance in several domains, including food safety, environmental monitoring, and medical diagnostics, is mostly dictated by a few key parameters. Since they specify the biosensor's capacity to identify trace amounts of a particular analyte in the presence of a complicated background, sensitivity and selectivity are crucial [43]. Another important consideration is response time, especially in real-time and clinical applications where prompt detection is essential. Reproducibility and stability guarantee steady performance over time and under many circumstances. Furthermore, the smallest quantity of analyte that can be accurately measured is indicated by the limit of detection (LOD).

Biocompatibility, particularly for in vivo applications, and linear range, which specifies the concentration range across which the sensor produces accurate readings, are additional crucial criteria. All together, these parameters determine the biosensors' applicability, efficiency, and dependability in a variety of sectors.

### 2.2.1 | Selectivity

The biosensor's selectivity refers to its capacity to differentiate the target analyte from other chemicals. High selectivity guarantees precise results free from influence in domains like clinical diagnostics and food safety, where samples may contain a wide variety of chemicals. Selectivity is a very important feature, especially in medical applications, where the test sample or sample matrix, usually blood or urine, contains numerous molecules that are quite similar to the target analyte and compete for binding to the biological receptor [44, 45].

### 2.2.2 | Sensitivity

Sensitivity describes the biosensor's capacity to identify analyte concentrations as low as possible. Small variations in the target analyte's concentration should ideally cause a biosensor to produce a signal. Biosensors must be able to detect analytes in the ng/mL or fg/mL concentration ranges, depending on the

application. High sensitivity is essential for environmental sensing to track pollutants at trace levels or for medical diagnostics to detect diseases in a timely manner [46].

### 2.2.3 | Response time

This is the speed at which the biosensor yields a result following exposure to the analyte; rapid response times are particularly crucial in on-site testing or emergency diagnostics where prompt results are needed.

### 2.2.4 | Limit of Detection (LOD)

The lowest quantity of analyte that the biosensor can consistently detect is known as the limit of detection, or LOD. For applications like water quality monitoring or cancer biomarker identification, a lower LOD indicates that the biosensor can detect very low quantities [47].

### 2.2.5 | Stability

It is the ability of the biosensor to tolerate changes in the environment, both within and outside the biosensing apparatus. Any disturbance could change the measuring output signals from the biosensor, leading to inaccuracy and a decrease in its efficacy. The electronics and transducer's sensitivity to temperature may interfere with the biosensor's ability to function. Therefore, accurate tuning is crucial to ensuring a biosensor's stable output. Another factor that may impact the biosensor is the analyte's binding affinity for the bioreceptor. The biosensor needs to be incredibly steady in order to overcome these issues [48].

### 2.2.6 | Biocompatibility

Biocompatibility is crucial for biosensors used *in vivo*, or inside the human body, in order to avoid negative reactions [49]. This is particularly important for biosensors used for ongoing health monitoring or implanted glucose sensors.

### 2.2.7 | Selectivity of Biosensors

The selectivity of a biosensor probably describes the capacity of a biosensor in order to differentiate a particular analyte from a combination of complicated compounds and therefore is mostly determined by molecular recognition components. These elements, which include molecularly imprinted polymers, enzymes, and antibodies, are made to selectively attach to a target analyte in a mixture of other molecules [50]. The recognition elements, such as enzymes, which are broadly used because of their high specificity for their substrate, while the antibodies also offer high selectivity due to their antigen-binding sites, which makes them suitable for identifying particular infections, biomarkers, and even other infections. Nucleic acid-based probes, such as aptamers and DNA/RNA sequences, allow for the sequence-level detection of genetic material and can be tailored for a variety of targets. Antibodies exhibit extraordinary selectivity

in their recognition of antigens. The potential for stable, reliable, and affordable substitutes for biological molecules has increased due to recent developments in synthetic recognition elements such as molecularly imprinted polymers (MIPs). Artificial intelligence and biosensors have transformed biomedical diagnostics by making it possible to quickly, accurately, and portably identify a variety of biomarkers. Particularly, chip-based biosensors have drawn a lot of interest because of their small size, affordability, and capacity for high-throughput research.

Biosensors have been used for a long time, but over the past few years, and it has got more importance and have been an immense game changer in many fields.

Recent advances in biosensors have completely changed almost every domain, including biotechnology, food safety, healthcare industries, and environmental monitoring. Development in data analytics, material science, and nano technology are driving the development of more sensitive, selective, and portable modern biosensors. The designs of these biosensors have made substantial use of nanomaterials, which include metal-organic frameworks, carbon nanotubes, and graphene, which improve signal transduction and make it possible to detect minuscule amounts of biological substances. Additionally, advancements in synthetic biology have made it possible to construct extremely selective bioreceptors, including enzymes, aptamers, and antibodies, which are specially designed to detect certain diseases or biomarkers. Blood sugar levels, hydration levels, and even early infection indicators can now be continuously and can be real-time monitored because of the development of wearable biosensors, which are integrated into clothing and skin patches [51]. A list of some of the biosensors has been tabularized in Table 1, given below.

## 3 | Biosensors in the Various Fields

### 3.1 | In the Medical Field

Biosensors have also become an important tool for the detection of cancer, as it offers high specificity, sensitivity, and also rapid diagnostic capabilities, making it suitable for detecting the disease. These sensors can detect biomarkers such as DNA mutations, Proteins and circulating tumor cells that are present in the saliva, blood, or other samples from the human body, which are indicative of different types of cancers. It can detect cancer at an early stage, providing an advantage to start the treatment from an initial stage. Optical biosensors are one of the types of sensors which uses light based detection in order to detect cancer biomarkers [54].

These sensors also help to detect infectious microorganisms like bacteria, fungi, or their toxins in blood, urine, and saliva in order to detect infectious diseases. The most deadly infectious disease of the 21st century, COVID-19, could also be detected by the electrochemical biosensors, which measure the electrical signals and their different components capture the virus, convert the interaction into an electrical signal, modify with nanomaterials for sensitivity, and ultimately analyze and display the results.

**TABLE 1** | Features, applications, limit of detection (LOD), and limit of qualification (LOQ) of different biosensors.

| <b>Types of biosensors</b>   | <b>Key features</b>   | <b>Applications</b>   | <b>Range of Limit of Detection(LOD)</b>  | <b>Range of Limit of Quantification(LOQ)</b> | <b>References</b> |
|--|---|---|--|--|-------------------|
| Nanomaterial-based biosensors  | High sensitivity, selectivity, repeatability, reaction time with good flow, and great detection range are some key features of nanomaterial biosensors. | These biosensors enhance detection capabilities by using nanomaterials such as dendrimers, metal oxide nanoparticles, carbon nanotubes, nanowires, nanorods, and quantum dots, which ultimately provide extensive applications in various fields. | The commonly reported LOD is $10^{-15}$ – $10^{-9}$ M                          | $10^{-9}$ – $10^{-6}$ M.                     | [27]              |
| Microbial biotechnology alchemy: Transforming bacterial cellulose into sensing disease   | High mechanical strength, high water absorption capacity, and high degree of crystallinity are some of the main features of bacterial cellulose.        | The features of bacterial cellulose ultimately result in its applications in different fields like wound dressing, cosmetics, food, and even as a filtration system.  | $4.26 \times 10^{-18}$ g mL <sup>-1</sup> S P                                  | ~3pM–300pg/mL                                | [23–25, 52]       |
| Microalgal Biosensors  | Microalgae's features include their great photosynthetic efficiency and adaptability, which make them valuable for different applications.              | The applications include the detection of harmful toxins and different pollutants that would benefit the environment, which would ultimately benefit living things.   | 0.1 nM to 10 $\mu$ M   | 0.3 nM to 30 $\mu$ M                         | [27]              |
| Biosensors based on aptamer-Conjugated gold nanomaterial                                 | High stability, ease of surface functionalization, and adjustable shape are a few key features of Aptamer-conjugated gold nanomaterials.                | Due to their stability, biological compatibility, adjustable shape, size dispersion, and simplicity of surface functionalization, these materials are ideal for targeted recognition, detection, and therapy.                                     | 1 fM–100 cfu/mL  | 3 fM–300 cfu/mL                              | [30]              |
| Recent advancements in electrochemical biosensors for the detection of cancer biomarkers | These biosensors detect cancer biomarkers with great sensitivity and accuracy.  | Applications of cancer biosensors include early cancer detection and monitoring, and provide more precise cancer cell identification.   | ~0.1 pg/mL–10 fg/mL  | Estimated at 0.3 pg/mL–30 fg/mL              | [32, 33]          |
| Cholesterol biosensors   | The key features includes accurate and rapid response time of approximately 1–300 s.  | The purpose of cholesterol biosensors is to detect the amount of cholesterol in a number of samples, including blood, fruit juices, drinks, serum, and urine.   | Enzymatic:- 0.1–10 $\mu$ M Non-enzymatic/nano-enabled:- 0.01 $\mu$ M-1 $\mu$ M | Usually ranges from 0.3–30 $\mu$ M           | [27]              |

(Continues)

TABLE 1 | (Continued)

| Types of biosensors                  | Key features   | Applications   | Range of Limit of Detection (LOD)      | Range of Limit of Quantification (LOQ)                                     | References |
|--------------------------------------|--|--|--|--|------------|
| Biosensors for wastewater monitoring | Sensitivity, selectivity, real-time monitoring, miniaturization, and cost effectiveness are the features.  | Their applications include the detection of a variety of contaminants and microbes present in water.   | $10^{-12}$ – $10^{-6}$ M               | $10^{-6}$ – $10^{-4}$ M.   | [42]       |
| Chip-based Biosensors                | Features include reduced quantity of sample requirements that improve sensitivity, analysis speed, and selectivity, as well as increased sensitivity brought about by microfluidic chip integration. | The applications of these biosensors include cancer detection, neurodegenerative disorders, drug discovery, and even infectious disease detection. | Usually ranges from 1pg/mL to 10 ng/mL | ~10× LOD, typically picomolar (pM) to low $\mu$ M or 10 pg/mL to 100 ng/mL | [53]       |

In addition to their quick, precise, and frequently real-time diagnostic capabilities, biosensors have become essential instruments in contemporary medicine. How diseases are identified, tracked, and treated has changed as a result of their incorporation into healthcare.

Biosensors are getting smaller, smarter, and more integrated with AI, IoT, and mobile platforms as technology advances, opening the door to predictive and individualized healthcare.

Biosensors are essentially catalysts for a more intelligent, quicker, and connected future in medical science rather than merely diagnostic tools.

Biosensors for biomarkers in medical diagnostics. The development of biosensors is arguably one of the most promising approaches to addressing some of the issues pertaining to the growing demand for highly sensitive, quick, and affordable analysis techniques in medical diagnostics [55]. Plasmon Resonance at the Surface Clinical Biosensors for Medical Diagnostics: The sensing research community frequently aims to get clinical samples. The plasmonic techniques of surface plasmon resonance (SPR), localized surface plasmon resonance (LSPR), and imaging SPR are maturing to the point where they can be used to monitor biomolecules in clinical samples. The earliest instances of monitoring proteins, enzymes, antibodies, etc. [56]. Features and applications of wearable biosensors in medical care. Wearable biosensors, one of the newest technologies in the medical industry, can monitor vital signs in patients, athletes, premature babies, youngsters, psychiatric patients, those in need of long-term care, the elderly, and those living in remote areas distant from medical facilities [57].

Biosensors for monitoring Glucose levels: Clinical applications for glucose biosensors are common for diagnosing diabetes mellitus, which necessitates exact regulation of blood glucose levels [58]. About 85% of the massive global market is made up of blood-glucose biosensors used at home [59]. “Wherever the art of medicine is loved, there is also a love of humanity.” With their transforming powers, biosensors exemplify this love, creating a mutually beneficial partnership between patients and healthcare providers where accurate diagnosis and individualized therapy work together to restore health and vitality [60].

### 3.2 | In Forensic Science

The ability to quickly, accurately, and on-site examine chemical and biological evidence makes biosensors crucial to modern forensic investigation. Enzymes, antibodies, or nucleic acids are examples of biological sensing elements that are combined with a transducer to transform a biological reaction into a quantifiable signal [61]. In forensic investigations, biosensors are commonly used to detect and analyze biological fluids, including blood, saliva, and semen, even in minute quantities or in compromised settings. Because DNA biosensors can identify certain genetic markers in extremely small quantities, they are particularly useful for assisting with self-identification and linking suspects or victims to crime scenes. Their portability and quickness lessen the need for time-consuming laboratory processes, enabling law enforcement to make decisions in the field more rapidly. As

biosensor technology advances and offers progressively more precise, automated, and portable solutions for criminal investigations, it is expected to play an increasingly significant part in forensic science. Forensic sciences employ a variety of biosensors.

However, there are drawbacks to mammalian biosensors that are not present in insect-based ones. Insects may be a preferred sensing technique in situations when using mammals is thought to be too risky. Dogs trained to find cadavers, for instance, are frequently put in hazardous situations where they may be exposed to hazardous substances or unstable objects. Since losing an insect sensor would be less costly than losing a trained dog, it would be beneficial to develop alternative sensing systems utilizing insects.

### 3.3 | In Sports and Fitness

Biosensors are progressively transforming the sports and fitness domains by enabling the non-invasive, real-time monitoring of different kinds of biochemical and physiological parameters by optimizing the performance, recovery, and overall health of an athlete.

Blood oxygen levels, heart rate, respiration, muscular activity, and other biological levels and changes in the body are all measured by biosensors. They transform these changes into electrical signals using a variety of technologies so that users can get real-time data.

The Wearable Biosensors that are integrated into wristbands or skin patches allow the continuous tracking of the sweat biomarkers, which are the key indicators of muscle fatigue, stress levels, and hydration levels. The lactate biosensors can detect muscle fatigue thresholds that help the athletes to adjust training intensity to avoid any kind of overexertion [62]

Another type of wearable biosensor is the cortisol-sensing patches, which provide a better understanding of physical or emotional stress that is crucial for balancing training and recovery [63]. By providing specific suggestions, these sensors improve decision-making about exercise scheduling, injury avoidance, and dietary consumption. Additionally, athletes participating in endurance sports benefit from glucose monitoring by avoiding hypoglycemia and maintaining adequate energy levels. The advancement in microfluidics has enabled the skin mounted sensors development which collects the athlete's sweat in situ without disrupting the movements.

Hence, biosensors are poised to become indispensable tools in personalized sports medicine, performance analytics, and fitness.

### 3.4 | Pollution Prevention With Affinity Electrochemical Biosensors

Electrochemical DNA-based disposable biosensors have been used to identify low molecular weight substances that have a strong affinity for nucleic acids. In order to create a straightforward tool for quick screening of genotoxic or related substances, the application relates to the molecular interactions between the

surface-linked DNA extracted from calf thymus and the target contaminants or medications [64].

### 3.5 | In Agricultural Field

Biosensors play a crucial role in modern agriculture, enabling the development of sustainable and efficient farming practices. These analytical devices convert biological signals into electronic signals, allowing for the detection and measurement of various components in agricultural samples [65]. Global issues that humanity faces include climate change and population growth, which affect agricultural and food safety. Climate change, soil erosion, pest outbreaks, and the requirement for sustainable farming methods are all posing increasing challenges to agricultural productivity. As a result, biosensors have become a game-changing instrument for precision farming, allowing for the real-time monitoring of numerous biological and chemical characteristics in livestock, crops, soil, and water [66].

Biosensors have long been recognized as one of the most effective tools for offering solutions to these problems. By enabling ongoing monitoring or early disease outbreak detection that can be prevented, biosensors can support sustainable agriculture [67].

### 3.6 | In Food Quality Monitoring, Food Safety, and Processing

Biosensors are utilized for the detection of pathogens in food. The presence of *Escherichia coli* in vegetables is a bioindicator of fecal contamination in food [68]. *E. coli* has been monitored by employing potentiometric alternating biosensing systems to detect pH variations brought on by ammonia using potentiometric alternating biosensing systems [3]. One promising strategy to improve food safety and quality assurance is the incorporation of biosensors into food quality monitoring systems. The management of food safety concerns across the supply chain is being revolutionized by biosensors, which allow for the quick, precise, and on-site detection of pollutants [69]. The rising demand for high-quality food has spurred academics and researchers to continuously innovate and create accurate, real-time food quality monitoring methods. Biosensors are one such tool that has surfaced and has already been extensively studied.

### 3.7 | In Plant Biology

The applications of biosensors have also been studied in the field of plant biology by detecting pathogens and monitoring various physiological processes. Plant research has advanced as a result of remarkable new technologies in the fields of DNA sequencing and molecular imaging. The position and dynamics of enzyme substrates, receptors, and transposons were not well-defined by conventional mass spectroscopy techniques, despite their unparalleled precision in measuring ion and metabolite levels and gaining insights into cellular and subcellular localization. Biosensors, however, make it simple and successful to tap this data [70].

Abiotic stress, the metabolic content, phytohormones, miRNAs, bacterial, viral, and fungal plant infections, genetically modified plants, and other substances can all be detected by these biosensors [53]. These sensors can also help to track the uptake of nutrients and their distribution, particularly for phosphate, potassium, and nitrate. When their integration is done with the aptamers or nanomaterials, they can detect specific pathogens or toxins that are released during any kind of infection. Moreover, biosensors detect the key metabolites such as lactate and glucose, which are essential for understanding the metabolism of plants. Hence, in plant biology Biosensors are now an essential tool for the non-invasive, sensitive, and real-time measurements of a wide range of biochemical and physiological characteristics in plants.

Overall, these biosensors are a flexible instrument in the realm of plant biology that can offer important information about the physiology, growth, and reactions of plants to external stimuli.

### 3.8 | In Fermentation Processes

The safety and quality of a product in the fermentation sector are crucial step. Hence, proper monitoring of the fermentation process is essential to optimize and maintain quality and safety. Biosensors can be used to detect process conditions indirectly by tracking the presence of products, biomass, enzymes, antibodies, or by-products. Because of their robust selectivity, low cost, easy automation, and straightforward instrumentation, biosensors precisely regulate the fermentation sector and yield repeatable results [3]. Biosensors help in making timely adjustments to the fermentation process by providing continuous data, which ultimately increases efficiency and reduces waste. Biosensors can be employed in a variety of fermentation processes, such as lactic acid fermentation (used in the manufacturing of yogurt and cheese) and alcoholic fermentation [53]. Biosensors are useful for process enhancement and quality control because they can identify and measure metabolites, including glycerol, lactic acid, and ethanol.

### 3.9 | In Metabolic Engineering

Though biosensors have a role in medicine, agriculture, and plant biology, they are also related to metabolic engineering. Since they allow the real-time monitoring of environmental signals and cellular health, biosensors are essential to metabolic engineering [53]. Metabolic engineers can alter processes or organisms to lessen or eliminate toxicity by using biosensors that can identify harmful metabolites. According to researchers, metabolic engineering is the technology that will make a sustainable bioeconomy possible [53]. Since genetically encoded biosensors link metabolite sensing to quantifiable outputs, they enable the quick screening of high-producing microbial strains. Biosensors improve the efficiency of bio-based manufacturing processes by helping to discover and optimize important enzymes and pathways [71]. Biosensors can be designed to express a gene required for survival under specific conditions, combining the detection of a desired product or intermediate metabolite with a fitness advantage for the cell [72]. Biosensors enhance target chemical production yields, optimize metabolic pathways, and enable high-

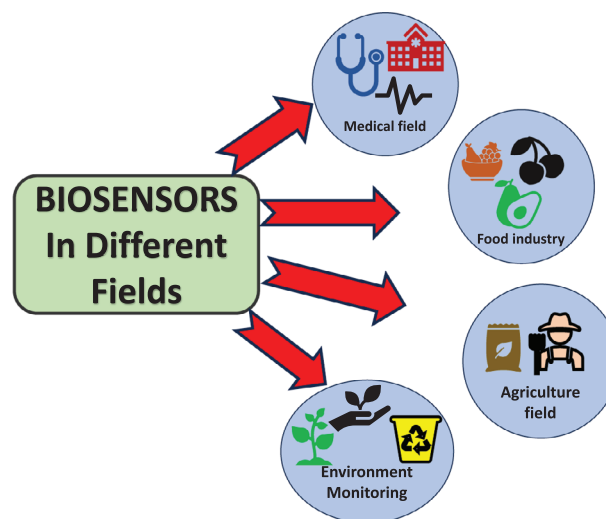


FIGURE 4 | Biosensors in different fields that benefit mankind.

throughput screening in synthetic biology by offering dynamic feedback. They are essential tools for designing effective and responsive biotechnological systems because their incorporation into metabolic networks enables precise regulation and adaptation. Overall, Biosensors are multipurpose instruments that offer precise, up-to-date information in a variety of domains. There are various types of biosensors, and these different types of biosensors have their roles and applications that all together help in benefiting mankind. Figures 4 and 5 depict the role and applications of biosensors, respectively.

### 3.10 | In Space and Aerospace

In aerospace and space, where the health and safety of astronauts during the extended flight period depend on real-time, portable, and extremely sensitive diagnostic devices, biosensors have become an important tool. Continuous health monitoring is necessary in the microgravity environment of space due to physiological changes include fluid redistribution, immunological suppression, muscle atrophy, and bone density loss. To measure stress levels, immunological reactions, and metabolic alterations, biosensors can identify a variety of biomarkers, such as cortisol (stress hormone), creatine kinase (muscle damage), cytokines (inflammation), and electrolytes [73]. These sensors for in-flight diagnostics have also been included in lab-on-a-chip platforms and wearable sensors, eliminating the need for intrusive sampling. NASA's BioSentinel mission, for example, studies DNA damage in yeast cells exposed to deep space radiation using biosensor technology to better understand the biological effects of the radiation [74].

Biosensors may also track the environmental factors like Carbon dioxide levels, air quality inside the spacecraft, and any kind of microbial contamination, in order to provide a safe environment for the astronauts and the crew members [75].

They are perfect for space missions with limited resources and space because of their small size, low power consumption, and ability to transmit data remotely. Biosensors will be crucial for allowing closed-loop life support, autonomous health

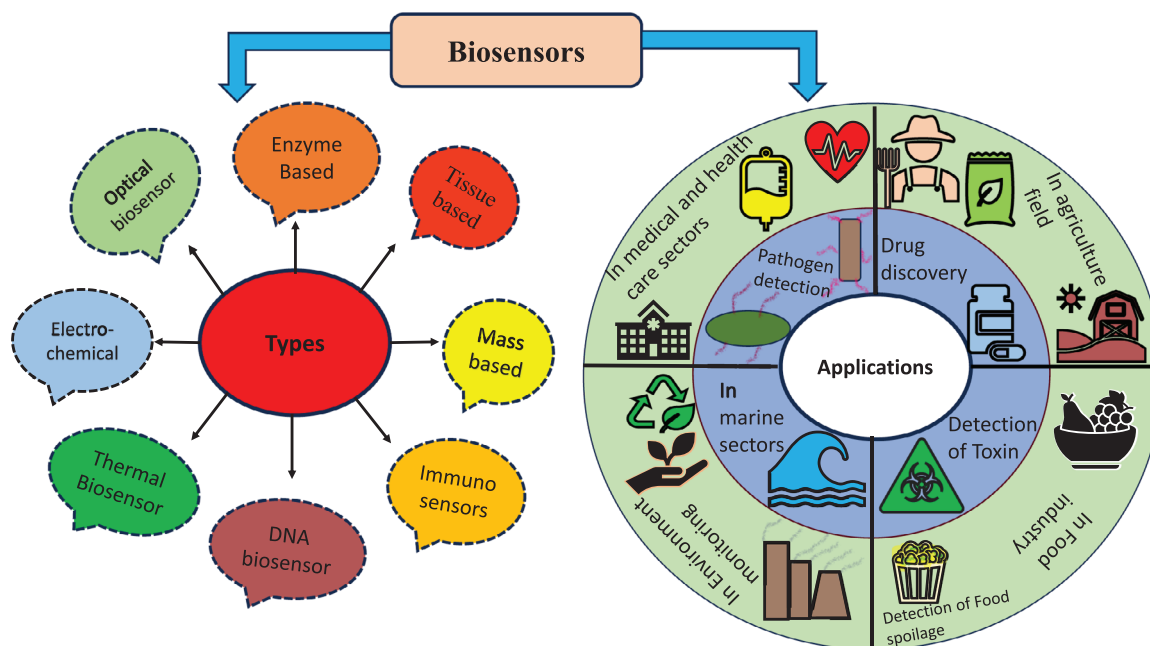


FIGURE 5 | Types of biosensors and their application in various sectors.

monitoring, and precision medicine in space exploration as future missions strive for Mars and beyond.

#### 4 | Future Prospectives

Biosensor applications have a very promising future owing to the continuous development in biotechnology, nanotechnology, and artificial intelligence. They have the potential to revolutionize healthcare in the upcoming years by facilitating preventive and highly effective medicines. Future biosensors may enable ongoing treatment of chronic illness, including diabetes, cancer, and cardiovascular conditions, early molecular disease identification, and real-time monitoring of critical biomarkers. Biosensors that can quickly identify contaminants, pathogens, and hazardous substances in water, soil, and air are a promising development in the environmental field that will even support international initiatives for environmental preservation and sustainability. Likewise, combining biosensors with big data analytics and machine learning will pave the way for intelligent systems that can foresee health trends, food safety issues, and environmental hazards before they materialize. By making it easier to identify chemical and biological weapons easily and quickly, future defense-related biosensors could enhance national security. As these gadgets get more affordable, smaller, and therefore more sensitive, they will be incorporated into everyday life more and more. This will contribute to the development of a future where biological data in real time informs healthier lifestyles, safer environments, and better-informed decisions on a global scale.

#### 5 | Conclusion

Biosensors have really evolved into quite strong analytical tools with a wide range of possible uses. By combining biological com-

ponents with state-of-the-art electronic technologies, biosensors enable the rapid, accurate, and sensitive detection of chemicals and biological materials. Their applications are numerous and include environmental monitoring, which ensures the safety and quality of air, soil, and water, as well as medical diagnostics, which allow for early illness identification and real-time health monitoring. Wearable technologies and point-of-care testing kits have allowed early disease detection, ongoing chronic condition monitoring, and tailored therapy to be all feasible.

Additionally, the recent developments in nanotechnology, micro-fabrication, and data analysis have greatly improved the performance and accessibility of biosensors, making them more portable, affordable, and easy to use. The wearable technologies and point-of-care testing kits have allowed early detection of disease and tailored therapy to be feasible. As research advances, biosensors are anticipated to be progressively more incorporated into daily life, supporting enhanced industrial operations, sustainable environmental practices, and intelligent healthcare systems. The pharmaceutical industry and biotechnological sectors depend on sensors for the development of drugs and quality control as much as the food sector does for the detection of impurities and food safety assurance. As biosensors are versatile and are constantly improving, they are an essential tool for solving some of the most significant issues confronting contemporary civilization, and therefore, their applications are expected to expand even further, playing an important role in addressing global challenges and advancing various industries and fields toward smarter and more responsive solutions.

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## Conflicts of Interest

The authors declare no conflicts of interest.

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