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REVIEW

Recent advancements in nanotechnological approaches for pollution monitoring and environmental sustainability

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Abstract

Environmental pollution and human health are inextricably linked. As the number of environmental pollutants increases, it is increasingly important to develop unique, effective, and intelligent analytical devices to monitor them. Biosensors are devices that capture biological signals and convert them into audible electrical impulses. To detect and observe specific biological analytes, such as the interaction between antibodies and antigens, biological entities such as DNA, RNA, and proteins/enzymes must be integrated with electrochemical transducers. Variety of biosensors has lately gained prominence and is being employed as in situ, real-time, and cost-effective analytical devices for healthy environments. Continuous environmental monitoring necessitates the use of biosensing technologies that are portable, inexpensive, quick, and adaptive. Each sensor, on the other hand, stands apart in terms of selectivity, technique, sensitivity, detection restrictions, sensitizing materials, and speed. Each sensitive element has a distinct selectivity and detection limit based on its sensitivity. This review focuses on the distinguishing characteristics, efficient design, and effectiveness of several types of biosensors, with an emphasis on the detection of environmental contaminants. Accurate devices will also aid in the continuing, parallel investigation of the causes and discharge of environmental toxins from diverse industrial sectors. Furthermore, real-time monitoring has the added benefit of allowing on-site analysis of pollutant components before to discharge into the environment, which can assist reduce the waste of a variety of harsh chemicals and reagents. The goal of this review is to provide an overview of the most recent developments in the field of using biosensors to identify environmental pollutants. Biosensors based on enzymes, entire cells, antibodies, aptamers, DNA, and biomimetic sensors are described. We list their useful qualities as well as their relevance to the detection of various contaminants. Designing biosensors makes use of a number of detection principles, including amperometry, conductometry, luminescence, etc. They differ in terms of design, profitability, sensitivity, and quickness. Further research is necessary to create a powerful biosensor that can identify environmental contaminants in a multifaceted medium, with no prior time-consuming pretreatment or tedious preparation protocols.

Keywords Environmental contaminants · Bio sensors · Pollution · Enzymatic · DNA · Microbial biosensors

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Abbreviations

DNA	Deoxyribonucleic acid
RNA	Ribonucleic acid
YSI	Yellow spring instruments
DDT	Dichlorodiphenyltrichloroethane
POPs	Persistent organic pollutants
GO	Glucose oxidase
OPH	Organophosphorus hydrolase
PTE	Phosphotriesterase
AMP	Amperometric
Vol	Voltammetric
Col	Calorimetric
Imp	Impedimetric
AChE	Acetylcholine esterase
SELEX	Systematic evolution of ligands by exponential enrichment
CNTs	Carbon nanotubes
SPE	Screen-printed electrodes

Introduction

On account of excessive industrial expansion, global urbanization, and population growth, numerous dangerous compounds are released into the environment and are built up, becoming a significant environmental threat in the present era. Pollutants come in a wide variety of forms and are widely spread in the soil, air, and waterways. They can be chemical, physical, biological, radioactive, or any combination of these. All biological systems are affected, but the health and way of life of people are severely affected (Xiong et al. 2022). Since environmental safety and security are a major issue on a global scale, monitoring the environment and managing it are two of the top priorities for both the globe and Europe (Justino et al. 2017). Researchers are interested in learning more about long-lasting explanations for the environmental monitoring systems since controlling harmful substances is a vital step in the pollution restoration process. Pollutants are typically detected using the high sensibility and selectivity of classic chromatographic and spectroscopic methods (Deng et al. 2022; Li et al. 2021). However, these processes take a number of stages for sample preparation, are time-consuming, contain dangerous chemicals, and call for expert workers to operate the equipment.

Enhanced biosensing devices were created as a result of the requirement to use some quick, picky, sensitive, and accurate, in-the-moment technologies for identifying and screening contaminants. A transducer, a signal processing system, a display, and a bioreceptor are just a few of the distinctive components that make up a biodetection device (Wu et al. 2022; Dimitrievsaka et al. 2023; Kumar et al. 2023). The complete apparatus produces a measurable detection signal that is correlated with the analyte concentration in the target (Brunnbauer et al. 2021). The biochemical receptor identifies the chemical or biological ingredients from the analysed sample, and the transducing component converts the biochemical result into quantized electrical, thermalor optical signals. Currently, there is a significant curiosity in developing extremely efficient and accurate systems for pinpointing and filtering environmental contaminants. The biosensor consists of the same transducer and signal processing system as a sensor, with the exception of using a biological analyte (Trapananti et al. 2021; Kulkarni et al. 2022). The pollutant is discovered by a bioreceptor, and a transducer converts the sample into a quantifiable signal (Naresh and Lee 2021; Tovar-Lopez 2023; Cimen et al. 2023).

Historical overview on biosensors

Since M. Cremer discovered in 1906 that the electric potential that exists across parts of a liquid on opposite sides of a glass membrane is proportional to the concentration of an acid in a liquid, biosensors have been used to quantify chemical concentrations in biological samples. Despite this, in 1909, Soren Peter Lauritz Sorensen put up the idea of pH (hydrogen ion concentration), and in 1922, W.S. Hughes developed an electrode for measuring pH. The "Father of Biosensors" Leland C. Clark, Jr. invented the first "authentic" biosensor for oxygen detection in 1956. In 1962, he demonstrated an amperometric enzyme electrode for the detection of glucose, which is known as the "Clark electrode" and carries his name. Followed by amperometric enzyme electrode, in the year 1969, Guilbault and Montalvo, Jr. discovered the first potentiometric biosensor for detecting urea and the first commercial biosensor was developed by Yellow Spring Instruments (YSI) in the year 1975. For diagnostics and the development of biopharmaceutical product monitoring, biosensors have made considerable strides recently. In order to achieve desirable pharmacological effects in a label-free environment, biosensors are crucial tools (Bilal and Iqbal 2019; Andryukov et al. 2020; Gaviria-Arroyave et al. 2020)**.** They also help us better understand disease and the interactions between molecules. A typical biosensor comprises (a) bioreceptor, (b) transducer, (c) electronics, (d) display, and (e) an analyte (Fig. 1a, b). The procedure for biorecognition refers to the formation of a signal (in the form of heat, pH, light, plant or animal tissue, charge or mass change, and microbial products) during the interaction of a bioreceptor and an analyte. A transducer is an important key instrument that transforms the state of energy. It turns the biorecognition event into a quantifiable (electrical) signal that corresponds to the quantity or presence of a biological or chemical target. The amount of analyte–bioreceptor interactions is proportional to the number of electrical or optical signals generated by transducers.

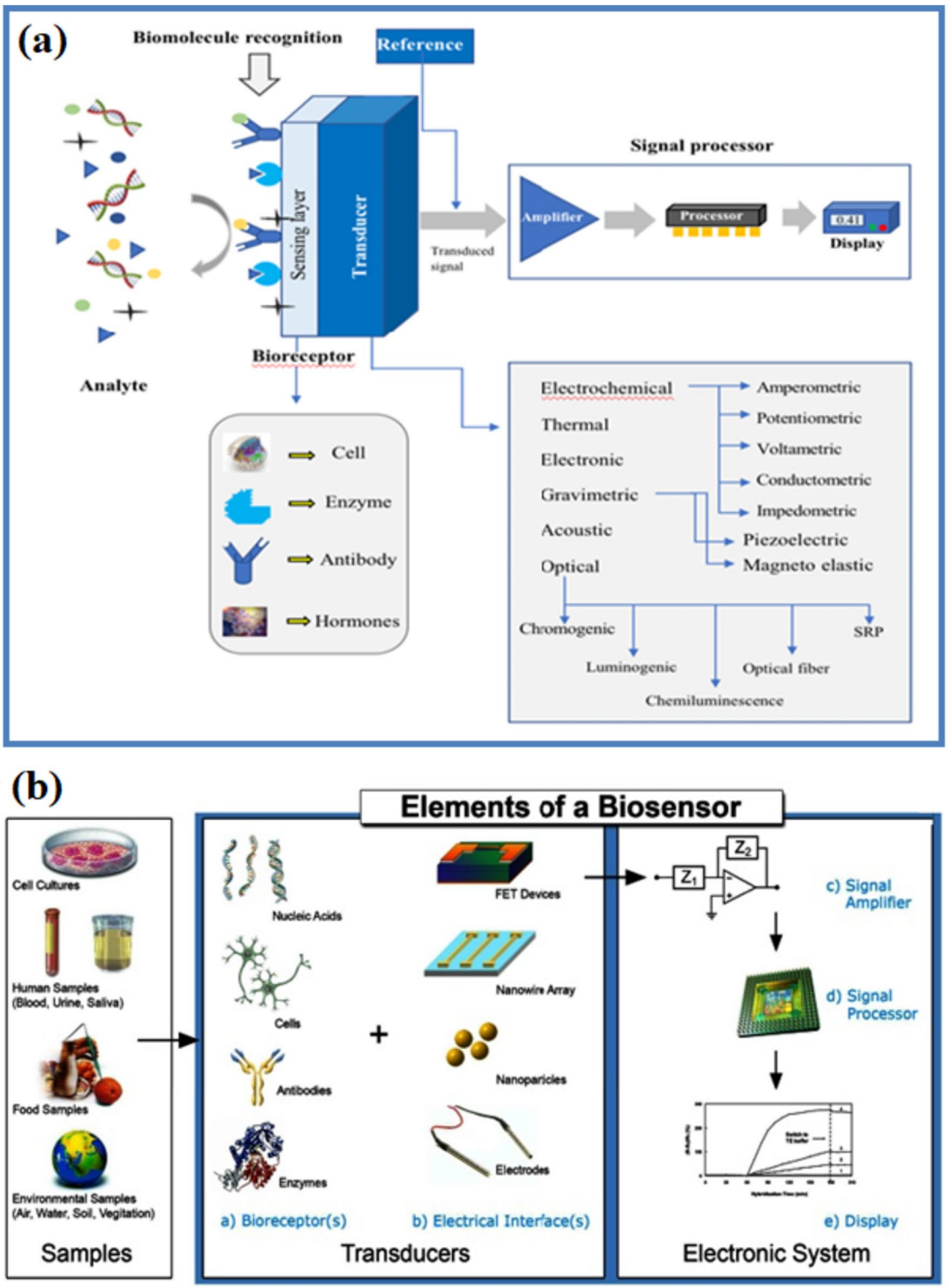

Fig. 1 (**a**) Schematic representation of Biosensor and (**b**) Elements of Biosensor (adopted from Grieshaber et al. 2008)

The electronics unit quantifies the transformed signals from transducer to a digital format. The display unit is made up of a user interpretation system which generates readable and understandable output (a numerical, tabular value, figure, or a pictorial representation).

Environmental impurities

Environmental pollution and its consequences, such as acid rain, ozone layer depletion, and climate change, are foremost worldwide concerns that are high on countries' economic and political agendas. Extensive use of chemicals in agricultural and industrial sectors has led to the discharge of potentially harmful contaminants into the environment. These pollutants represent major hazards to human health and ecological diversity due to their broad dissemination. Traditional chromatographic methods for detecting these environmental pollutants need expensive and specialized equipment, long detection reaction times, and user training. Furthermore, vital environmental variables such as cytotoxicity, bioavailability, mutagenicity, and genotoxicity can only be detected in living cells which is not always possible. As a result, sensitive, rapid, and cost-efficient surveillance of these harmful chemicals is necessary in pollution reduction programmes and management systems (Huang et al. 2023; Fatima et al. 2022). The most precise and sensitive methods for detecting environmental contaminants are biosensors (Patel et al. 2021). These devices create a detectable signal by fusing an electrical element with a biological component—either an enzyme or an antibody. The electronic component detects, records, and transmits information on physiological changes as well as the presence of chemical or biological elements in the surrounding environment. Due to the vast range of applications, including medical care and illness detection, water and food quality monitoring, and environmental monitoring, biosensors have thus assumed an inevitable stage in the last ten years (Willner and Vikesland 2018; Thakur et al. 2022). In general when the pollutants interact with DNA nanosensor to produce signal or to suppress signal. The type of signal may vary from light, electroactivity, pH change, mass change, and heat change upon interaction with pollutant in a concentration-dependent manner. The data are processed using a data processing system, and output is produced in a readable format.

Pesticides

In order to attain high agricultural productivity, pest management is currently accomplished through the purposeful application of a wide range of harmful compounds, known as pesticides, with significant environmental consequences. Around 3.42×10^6 t/y worth of insecticides were used globally in 2015. The assurance of the quantity and quality of food and feed justifies the use of these insecticides. The majority of pesticides are environmental pollutants with considerable negative impacts since some components are persistent in the environment and have extended half-lives, even when used in compliance with the law; only a tiny part of pesticides meet the stated targets. Pesticides like aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, and toxaphene are examples of POPs (persistent organic pollutants) because they take years to decompose. These POPs have the potential to alter the endocrine, reproductive, and respiratory systems of humans as well as non-target creatures in the environment. The automated, precise, and highly specific analytical methods for pesticide identification that integrate chromatographic techniques with various detectors are automated. These systems do have several drawbacks, though, including high costs, time demands, the need for sample pretreatment, and a slow response time. As a result, the study concentrated on creating biosensors, which are quick and accurate pesticide detection tools (Mirres et al. 2022; Samal et al. 2023). The essential idea of these biosensors, which are currently used in a variety of disciplines and businesses, is sample analysis and its recognition, transduction, and amplification.

Electrochemical immunosensors' high specificity and sensitivity have been used in pesticide detection applications. Mehta et al. (2017) described the invention of an electrochemical immunosensor for detecting the organophosphate insecticide parathion. The immunosensor was created by (i) adding graphene quantum dots to a screen-printed electrode surface, (ii) electrochemically functionalizing with NH_2 groups, and (iii) biointerfacing with anti-parathion antibodies. The biosensor has a logarithmic linear range of 0.01 to 106 ng/L and a LOD of 46 pg/L, and it was highly selective for parathion even at high doses (1000 ng/L) of other pesticides such as paraxon, malathion, and chlorpyrifos. Aside from its great sensitivity and selectivity, the immunosensor offered several additional advantages, including a quick response time (15 min), and strong repeatability. Multianalyte immunosensors, in addition to single-analyte detection, have been developed and demonstrated to be successful in the detection of pesticides such as endosulfan and paraoxon at low concentrations (0.05 and 2 ppb, respectively).

Perez-Fernandez et al. (2020a, b) created a direct competitive electrochemical immunosensor for the detection of imidacloprid, a neonicotinoid. Monoclonal antibodies were immobilized on a gold nanoparticle-modified screen-printed carbon electrode, with imidacloprid competing for antibody-binding sites with imidacloprid linked with horseradish peroxidase. The immunosensor had a low LOD (22 pM) and good precision (RDS of 6%), selectivity, and accuracy (relative error of 6%). It also had one-month stability.

Pharmaceuticals impurities

Despite the tight regulatory procedures followed before commercialization, several types of pharmaceutical pollutants gradually have an impact on ecosystems. Aquatic ecosystems tend to accumulate pharmaceutical contaminants more so than terrestrial ones. According to Lan et al. (2018), the sources of pharmaceutical pollutants include the production process, medications used on livestock, streams from animal feeding facilities, and excessive use of norcotic drugs including caffeine and cotinine. Pharmaceuticals accumulate in the environment as a result of improper industry removal and human excretion of unmetabolized medications. Figure 2 elaborates on the overview of how pharmaceutical impurities affect the environment and the ecosystem.

Amperometric biosensors monitor current flows created by an electrochemical reaction at a constant potential, where the intensity of the current is proportional to the concentration of the oxidized and reduced material on the electrode's surface. These biosensors have been used to quantify aminoglycoside antibiotics, bronchodilators (including theophylline), anti-arrhythmic medicines, and anticancer medications.

Huang et al. (2019) used a multilayer material to modify the glassy carbon electrode to explore the human umami taste receptor (hT1R1) and umami compounds such as monosodium glutamate (MSG). A human umami taste receptor (hT1R1) was linked to the layers generated by the AuNPs during the creation of this electrode. For direct electron transfer to the produced multilayer material, horseradish

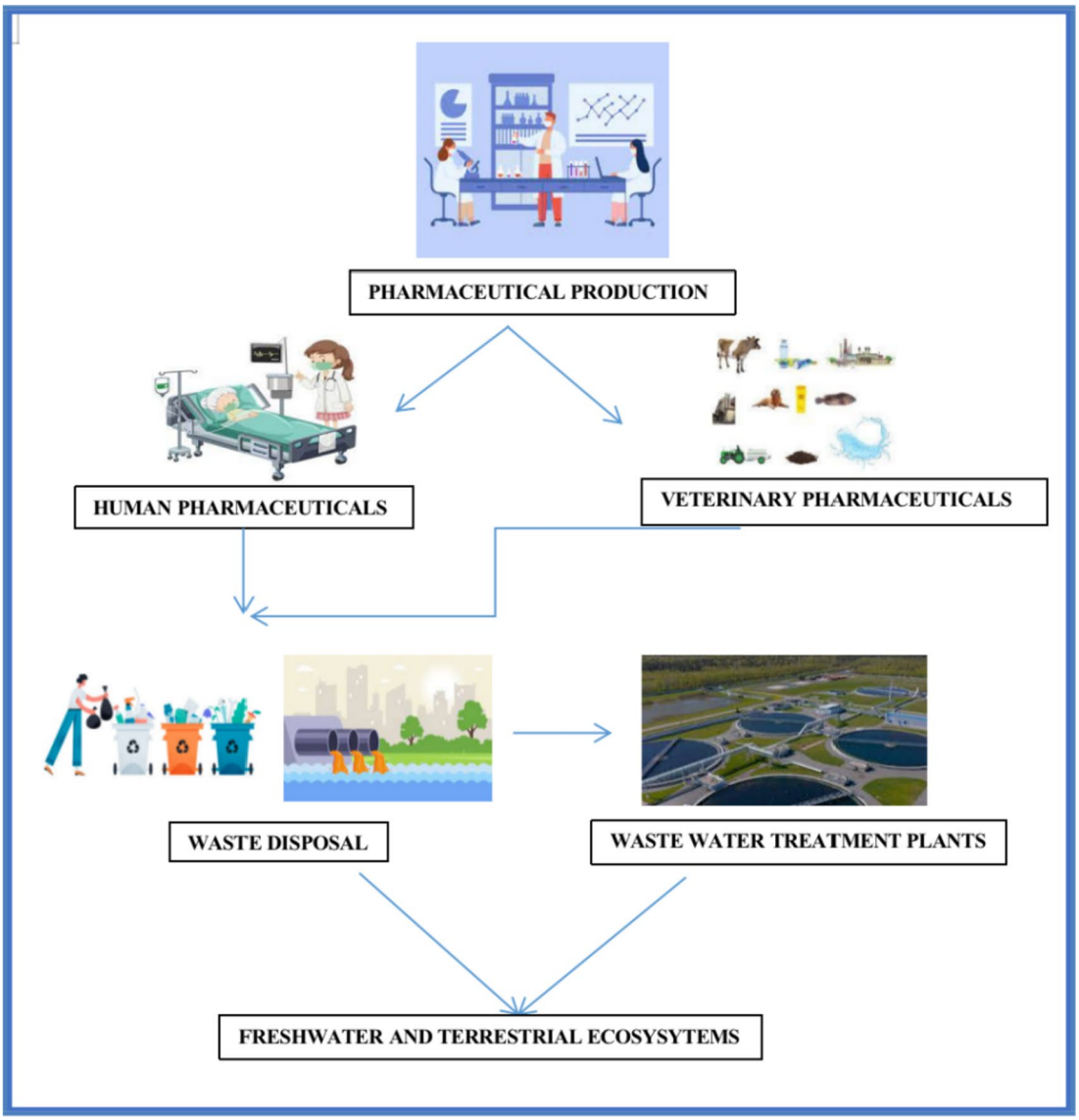

Fig. 2 Impact of pharmaceutical impurities on ecosystem

peroxidase (HRP) is utilized. The researchers believe that hT1R1 is a receptor used by the body to sense nitrogen, which opens up a new avenue of investigation into nutrition and medication adsorption (Mackulak et al. 2020; Wei et al. 2016).

The same researchers constructed another biosensor in 2023 by connecting colon cancer and nearby tissues to GCE in order to visualize the kinetics of responding to C and N nutritional receptors such as glucose and sodium lactate. They did this by combining solutions of starch gum, an aldehyde base, and sodium alginate and spreading them across two microporous polycarbonate membranes into which the colon tissues were put to form a layered assembly aligned with the GCE. Researchers discovered that the cells reacted differently to lactate, implying that this nutrient could be used to treat colon cancer. Lactate has no effect on colon cancer tissue, but it does on neighbouring tissue (Lu et al. 2023).

Heavy metals

It is generally known that mining and related engineering activities increase the build-up of heavy metals in water bodies. Heavy metals do not break down and accumulate in the environment for a very long time. Because reactive oxygen species are produced, the majority of heavy metals seem to have increased hazardous potentials (Yu et al. 2006). However, only a select few of them are needed to exert a variety of biological activations, such as enzyme-mediated reactions, as cofactors, to bring about inhibitory effects (Rebollar-Perez et al. 2016). Consequently, the specific key to designing biosensors for detecting heavy metals is either the induction or repression of enzymes. Alkaline phosphatase and ascorbate oxidase grounded biosensors may detect zinc and copper. A biosensor for detecting the presence of heavy metals such nickel, copper, cobalt, and cadmium was successfully demonstrated when glucose oxidase (GO) was suppressed (Ghicaet al. 2013). By achieving a reporter gene under the control of an inducible promoter for the detection of heavy metals, it was clarified (Rodriguez-Mozaz et al. 2006). According to the contaminants concentration, the reporter signal limits increases during this method. Common reporter genes used in the creation of biosensors include β—galactosidase, luciferase, and green fluorescent protein.

E. coli and the electrochemical redox mediator benzoquinone were co-immobilized within a gelatin/silica hybrid hydrogel on the surface of a glassy carbon electrode, according to Li et al. The toxicity of Hg^{2+}, Cu^{2+}, and Cd^{2+} ions was tested using this biosensor, with microgram per litre IC_{50} values reported. Its capacity to identify heavy metal ion combinations in laboratory wastewater has also been established (Hara and Singh 2021).

Types of biosensor

Enzyme biosensor

Due to their high selectivity, biological activity, and dependability, enzymes are biocatalysts and can be employed to detect pollutants and contaminants in the environment. By deactivating the pollutant or by catalysing its conversion to less hazardous metabolites, enzymes can detect contaminants. The amount of pollution in a sample can be determined using the signal produced during these procedures. The analyte (pollutant) is passed via the enzyme in the design of the enzyme biosensors, which immobilizes

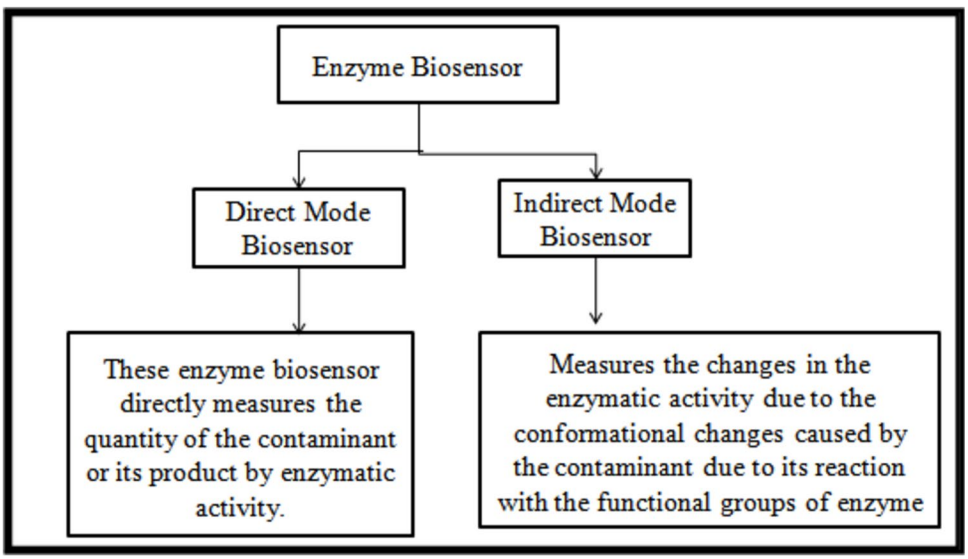

Fig. 3 Classification of enzyme biosensor

the enzyme on a transducer. The transducer transforms the signal produced by the process into a measurable value. Figure 3 following depicts the classification of enzyme biosensors (Wang et al. 2020).

For several applications, enzyme-based biosensors have been developed using enzymes including horseradish peroxidase, glucose oxidase, and alkaline phosphatase. The enzymatic biofuel sensor was created by Li et al. (2020). It is a self-powered sensor that is encapsulated with laccase enzyme to measure the concentration of bisphenol. The primary raw ingredient in plastics like polyvinyl chloride and polycarbonate is bisphenol, which is also a significant water contaminant. The pollutant could be detected by the biosensor even at a lower concentration of 1.95×10^3 mM due to its great effectiveness. Numerous enzyme biosensors based on enzymes like acetylcholine esterase, butyrylcholinesterase, phosphotriesterase (PTE), and organophosphorus hydrolase (OPH) have been developed as a result of the capacity to detect organophosphate. The idea behind these sensors is to benefit from phosphorous' ability to reduce acetylcholine esterase activity. The cholinergic substrate cannot be hydrolysed by the enzyme because the serine residue in the active core of the enzyme binds to phosphorus (Wang et al. 2020). Some of the enzyme biosensors for measuring pollution are included in Table 1.

Table 1 Enzyme-Based Biosensors to Detect Environmental Contaminants

Detection contaminants	Developed Biosensor	Biorecognition materials used	Sensing component	Detection limit	% of recovery	References
Paraoxon	Amperometric (AMP)	Acetylcholine esterase	Screen-printed electrode with AU and cysteamine	2 ppb	97.5	Li et al. (2021)
	Voltammetric (Vol)	Butyrylcholinesterase enzyme	SPE added carbon sphere	5 Ug L^{-1}	96	Tschmelak et al. (2005)
	Calorimetric (Col.)	AChE enzyme	Starch-Iodine	4.7 ppb	88	Wu et al. (2022)
	AMP sensor	AChE	Gold nanorods	0.7 nM	98	Justino et al. (2017)
Methyl Parathion	Impedimetric	Hydrolase	Reduced graphite	0.1 ng mL^{-1}	–	Naresh and Lee (2021)
	Electro biosensor	Enzymatic participation AChE	Electrode with glue of carbon and a network of $NiCO_2SO_4$	0.42U gmL^{-1}	–	Bilal et al. (2019)
	Optical Biosensor	*Sphingomonas* sp.	SiNPs and pE^{-6} hybrid	0.01 ppm	–	Hashem et al. (2021)
Chlorpyrifos	Imp. bio sensor	Tyrosinase	SPCE and IrOxNPs	3 nM	90%	Chung et al. (2021)
	Vol. Sensor	AChE	Diamond electrode doped with Boron + Gold NPs added carbon beads	0.13 pM	82.4%	Jain et al. (2022)
	Amp. Sensor	AChE	GCE 5 with Nickel Oxide NPs Carboxylic grapheme Nafion	0.05 pM	93–105	Chen et al. (2019)
Paraoxon	Electrochemical biosensor	Phosphotriesterase	Organophosphorus hydrolase and OPH nanocapsule immobilized on Graphene oxide	3 nM	–	Borah et al. (2017)
Dimethoate	Electrochemical biosensor	Glutathione S-transferase	Pt electrode	5 ppb	83	Nikbakt et al. (2018)
Pirimicarb	Vol. sensor	Laccase enzyme	Glue of carbon with multi wall CNTs	43 Ug L^{-1}	–	Porras and Maranon (2012)
Pirimicarb	Amp. sensor	AChE	Prussian blue mwCNT + SPE	53.2 ngL^{-1}	–	Tang et al. (2018)
Carbaryl	Electrochemical amp. sensor	AChE	Porous GCE with GO Web	0.74 nM	98.3	Asal et al. (2018)
Bisphenol A	Amp. sensor	Tyr	GCE	0.01 nM	–	Zhao et al. (2022)

Electrochemical biosensor

Biosensors are a good substitute for conventional chromatography-based approaches because they may be designed with incredibly precise recognition sites. Electrochemical biosensors are among the existing biosensors that have a number of benefits, including real-time monitoring, miniaturization, and improved selectivity and sensitivity. Additionally, electronic signals are produced by electrochemical processes rather than complex signalling components. This makes it easier to create portable devices for on-site environmental monitoring and clinical testing. Biosensors use electrodes to transform biological signals into readable output signals. By altering some biological components, such as DNA, enzymes, or cells, one can increase the selectivity and sensitivity of these signals. Based on the type of transducer, electrochemical biocatalytic sensors have been altered with biological components that may identify a target and cause an electroactive molecule (such as enzymes) to react. Electrochemical affinity sensors, on the other hand, have a binding recognition element that, when attached to the target (such as antibodies), releases a signal. Typical electrochemical biosensor components and their working are illustrated in Fig. 4a, b.

DNA biosensors

Biosensors use nucleic acids as its sensing elements, such as DNA or RNA. Nucleic acids, particularly single-stranded DNA (ss-DNA), are used as recognition components by the majority of DNA-based biosensors. A probe, which is often an artificial oligonucleotide with a specified sequence, and a signal transducer are hybridized to create biosensors in DNA biosensors. Immobilization and probe selection are crucial steps in the creation of DNA biosensors. There are two different action systems, like, (i) hybridization: through single-stranded nucleic acid that has been immobilized on a solid matrix, the analyte that is complementary to the DNA is transferred. The analyte and the nucleic acid combine. The target DNA and its complementary strand stop on the location of the sensing area as a result of an impulsive hydrogen bonding between adenine–thymine (A = T) and cytosine-guanine (C = G) pairs.(Kokkinos, 2019 and Saidur et al. 2017). This hybridization results in a conformational change in nucleic acid from single strand to double strand. A transducer converts the signal produced by this transition into a quantifiable form. (ii) The target analyte's molecule(s) altering the structure of the ss-DNA (Bacchu et al. 2022). These processes encourage a range of physicochemical changes, which results in the detection of a distinct signal that may be translated into a calculable response by a transducer; typically, optical or electrochemical sensors are used (Wang et al. 2022).

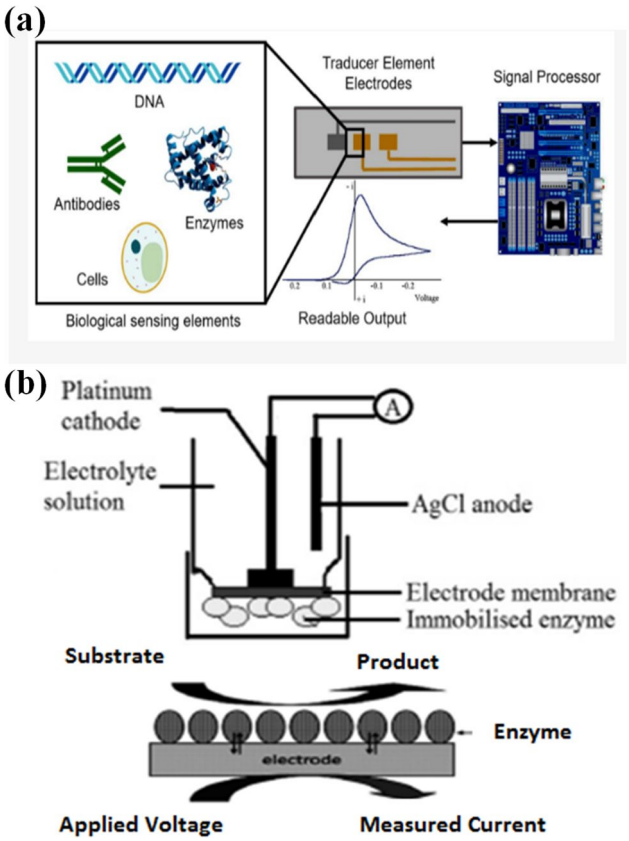

Fig. 4 **a** Scheme of an electrochemical biosensor. Biological sensing elements are coupled to electrodes. These traduce the signal to deliver a readable output and **b** Working of Amperometric biosensor (adopted from Hernandez-Vargas et al. 2018; Nigam and Shukla 2015)

A sensitive, sensitive, affordable, and trustworthy method for quantifying contaminants is using DNA biosensors. The metal ions in pollution are capable of binding the nucleotide bases, especially cytosine and thymine, effectively. In order to detect metal contaminants like copper, cadmium, and zinc, among others, C- and T-rich DNA can be used as a probe. DNA quadraplex, a guanosine-rich tetra helix DNA, can be used to detect lead, zinc, cadmium, salt, and phosphorous. The binding of these metals to the G-rich DNA causes a conformational change that generates a signal that can be detected. Figure 5 illustrates the basic principle of DNA biosensor.

DNAzymes, a kind of nucleic acids having catalytic activity, are frequently used as the biological sensing component in biosensors. DNAzymes have both catalytic and substrate-binding sites. The substrate-binding site's nucleic acid has a cleavage site. The amount of metal ions present can be determined by analysing the signal produced by the cleavage caused by metal ions such as manganese, magnesium, copper, lead, zinc, and cadmium. According to numerous researches (Bacchu et al. 2022; Sun et al. 2019a, b; He

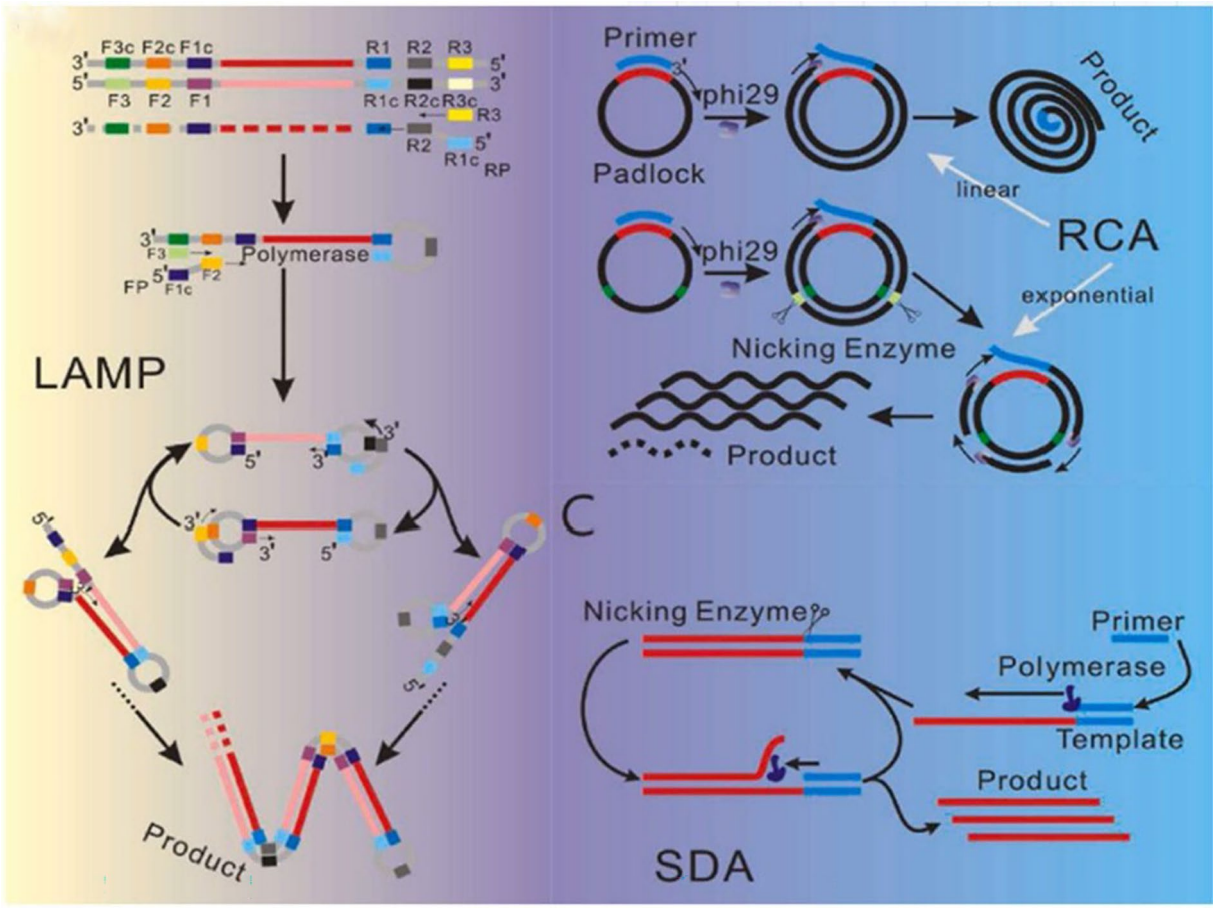

Fig. 5 Basic principle of the enzyme assisted DNA amplification reaction (adopted from Wang et al. 2022)

et al. 2020; Sun et al. 2019a, b), DNA-based biosensors can detect trace levels of heavy metals in the environment. The ability of some heavy metal ions to combine with particular DNA bases to form stable duplex structures forms the basis for the functioning of this system. For instance, the mercury ion (Hg^{2+}) binds thymine (T) bases specifically to produce a thermally stable T-Hg^{2+}-T duplex (Muhammad and Huang 2021). Similar to this, C–Ag^{+}-C base pairs are created when two cytosine (C) bases interact preferentially with silver ions (Ag^{+}), aiding in the stabilization of the DNA duplex (Wang et al. 2022; Bacchu et al. 2022). Thus, single-stranded DNA rich in thymine or cytosine can form stable structures that allow metals to be detected using the right transducers in the presence of some metal ions (Bacchu et al. 2022).

The fluorescence quenching of C-rich DNA coated with AgNCs and Cu/AgNCs has also been studied to develop innovative DNA nanosensors (Sun et al. 2019a, b; Muhammad and Huang 2021). Gold nanoparticles were functionalized with thymine-rich DNA templates containing FAM at the long end and undergoing fluorescence reduction in the presence of mercury in order to activate the collapsible DNA template, which brought up FAM in the vicinity of gold nanoparticles (Long et al. 2013). Gold nanoparticles and DNA have been combined to create a nanosensor that can pick up several metal ions at once. The affinities of specific metal ions on FAM-labelled DNA-AuNPs result in fluorescence quenching. Tetra chloroauric acid and hydroxylamine were added to AuNPs, which boosted the structure's selectivity by causing the external surface to diverge. The change in the external surface area of AuNPs suggested different colour development. Table 2 lists some of these sensors that are used to identify and address Ag^{+}, Hg^{2+}, Pb^{2+}, metals, and foodborne pathogens.

Aptamers biosensors

Like DNA and RNA, nucleic acids, also known as aptamers, are well-known genetic machines that pass on the genetic code to succeeding generations in living things like humans. Nucleic acids may have had a big role in the study of detecting environmental pollution; it has been hypothesized in recent years. The building blocks of aptamers, which preferentially draw inorganic or organic impurities,

Table 2 DNA-Based Biosensors to Detect Environmental Contaminants

Type	Pollutant	Mechanism	References
DNA sensor	Hg^{2+}	Formation of stable T-Hg^{2+}-T complex	Liu and Lu (2003)
DNAzyme	Pb^{2+}	In the presence of Pb^{2+}DNAzyme catalyses the breakage of bond between substrate and oligonucleotides, causing release of red colour	Taguchi et al. (2018)
DNA sensor	Ag^{+}	Formation of stable C–Ag^{+}-C complex	Liu and Lu (2003)
Fluorescent labelled cDNA Biosensor	Hg^{2+}	Folding of cDNA to hairpin shape, leading to the release of fluorescent tag, causing reduced fluorescence	Liu and Lu (2003)
17 β –estradiol DNA aptamer	17 β-estradiol	Binding of estradiol to DNA aptamer causes decrease in current due to redox reaction	Kim et al. (2007)
DNA Aptamer-based biosensor	*Campylobacter jejuni* (food pathogen)	The aptamer specifically bind to *Campylobacter jejuni* and release fluorescence. Aptamer-bound *Campylobacter jejuni* cells were sorted into different pools based on fluorescence intensity using flow cytometer	Dwivedi et al. (2010)
DNA sensor	$Hg2^{+}$	Mercury has the potential to initiate the activation of the T-rich DNA machinery, resulting in the substantial production of product DNA, thereby facilitating signal amplification	Huang et al. (2017)
RNA Aptamer-based biosensor	Microcystin (raw material for glue and plastics)	RNA aptamer binds with high affinity to Microcystin, even at a low level of 0.5 µM/L, causing an output signal	Cunha et al. (2018)
DNAzyme-based sensor	Na^{+}	Binding of sodium releases initiator DNA triggering output signal	Khan et al. (2021)

are deoxyribonucleic acid or ribonucleic acids. It has been discovered that certain genetic base pairs of aptamers can make it possible to build this kind of biosensors specifically. However, the primary technique for creating new aptamers is in vitro selections. Due to their distinct characteristics, aptamers are excellent candidates and high-quality materials for a variety of new sorts, including Systematic Evolution of Ligands by Exponential Enrichment (SELEX). The initial observation and description of this specific type of sensor device were made in 1990 (Zhuo et al. 2017; Ni et al. 2021).

Aptamers have special benefits such stability, improved enzyme resistance, high ionic strength, enhanced temperature or pH tolerance, increased attraction and specificity to target contaminants, and a size range of in vivo and in vitro sensors from nano- to pico-molar. In addition to not requiring synthesis in host animals or a traditional immune response, aptamers have additional benefits over antibodies. Single-stranded nucleic acid aptamers are combined with carbon nanotubes (CNTs) or grapheme sheets through non-covalent or hydrogen contacts to create aptasensors. A fluorescent signal results from the aptamers attaching to the pollutant in the presence of the pollutant and breaking the interaction between the aptamer and the grapheme (Flores-Contreras et al. 2022). A new composite film consisting of carbon black and graphene oxide Fe_3O_4 has recently been created as an electrochemical aptasensor for the detection of chlorpyrifos in agricultural samples. 94 pM was discovered to be the detection threshold (Perez-Fernandez et al. 2020a, b).

Microbial biosensors

In microbial biosensors, living or dead microbes that have been immobilized on a solid matrix serve as the sensing components. Genetic engineering makes it simple to modify microorganisms to increase their performance and tolerance. Microbial biosensors that have been genetically altered are employed in a variety of applications because they are accurate, cost-effective, portable, and tiny. The main drawbacks of microbial biosensors, however, are their extended recovery and response periods, high sensitivity to temperature and pH, and hysteresis effect.

In comparison with conventional methods, whole cell-based microbial biosensors are shown to be more effective in sensing environmental signals. This is because they can operate under a variety of working conditions. In numerous studies, earthly and aquatic living creatures have been used as microbial biosensors to identify environmental contaminants including pesticides, heavy metals, phenols, and other harmful substances (Vanitha et al. 2017; Gupta et al. 2019; Do et al. 2022; Nigam and Shukla 2015). Regulatory genes and reporter genes are examples of biological recognition components in microbial biosensors. Figure 6 displays the role of regulatory and reporter genes.

Bacterial biosensors are now useful for the detection of heavy metals in environmental tests thanks to the adoption of appropriate genes as bioreceptor that are resistant to detected metals. Many bacterial structures have been recognized as potential biological receptors for heavy metals like zinc,

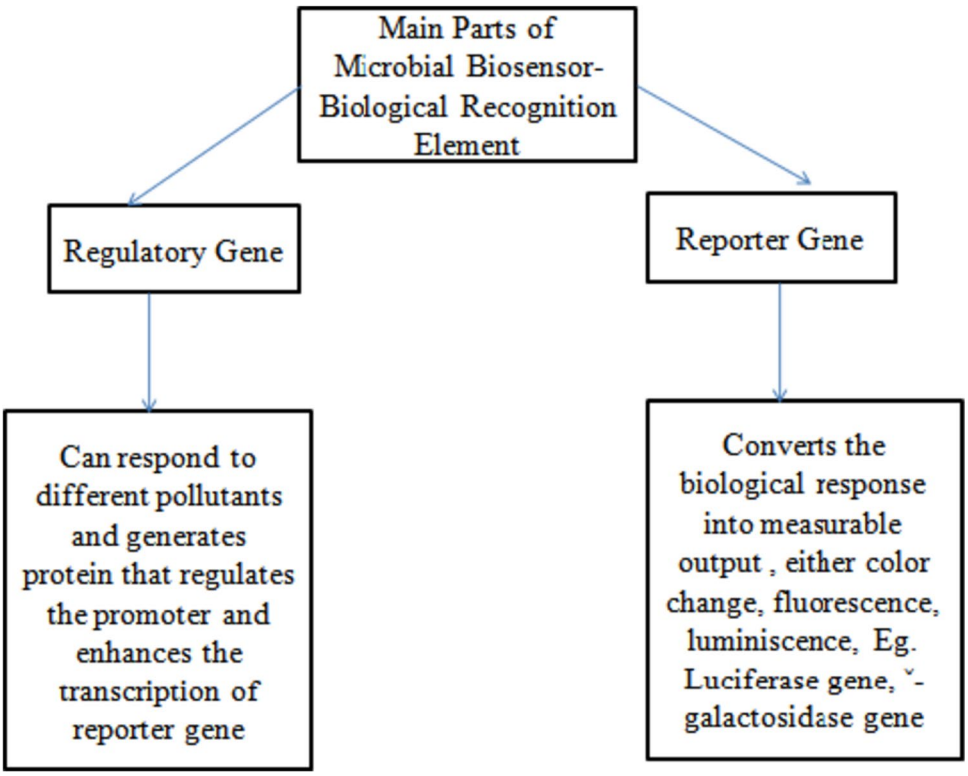

Fig. 6 Classification of biological recognition elements in microbial biosensor

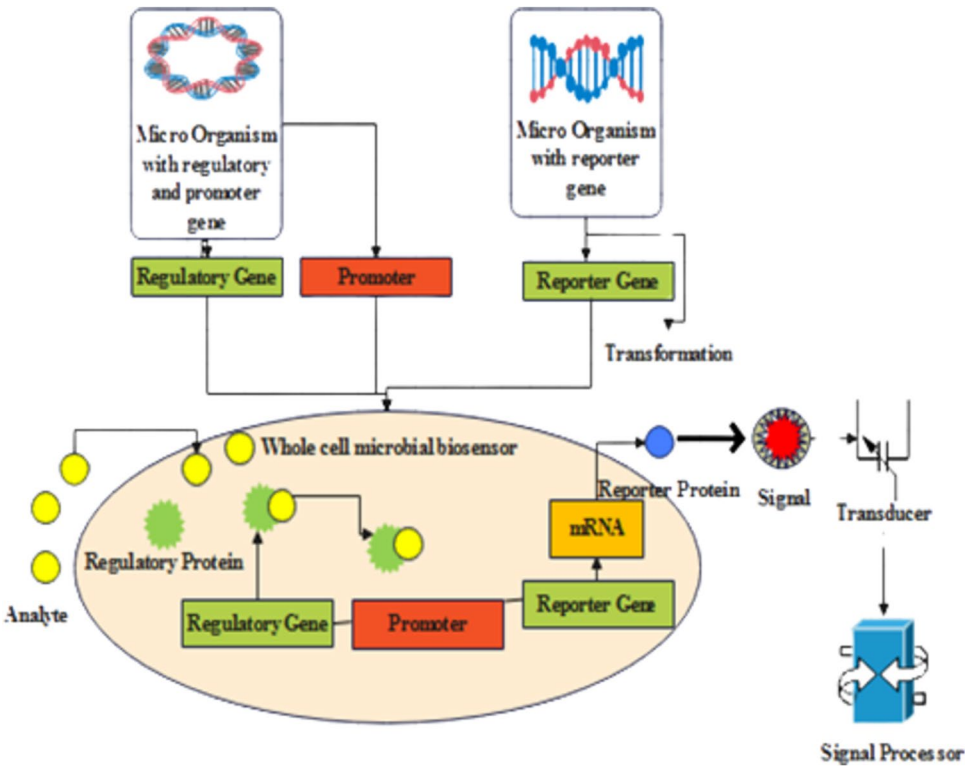

Fig. 7 Design and working of microbial biosensor

Table 3 Microbial biosensors to detect environmental contaminants

Pollutant	Microorganism	Transducer	LOD	References
As^{3+}	Genetically engineered *S. oneidensis*	Electrochemical	40 µM	Webster et al. (2014)
Cu^{2}	*Saccharomyces cerevisiae*	Colorimetric	1 µM	Vopalenska et al. (2015)
Cd^{2+}	Genetically engineered *Escherichia coli*	Optical	0.01 ppm	Iravani and Varma (2022)
Ni^{2+}	Ralstonia eutropha strain AE2515	Optical	0.1 µM	Kim et al. (2016)
Pb^{2+}	Genetically engineered *Escherichia coli*	Optical	5 ppm	Jeon et al. (2022)
Cd^{2+}	*Bacillus megaterium* VR1	Fluorescent	1.42×10^{-4}	Gavrilaș et al., (2022)
Pb^{2+}	*E. coli*	Fluorescent	<30 µM	Jeon et al. (2022)
Zn^{2+}	*Bacillus megaterium* VR1	Fluorescent	2.42×10^{-4}	Bhatt and Maheshwari (2020)
Paraoxon	Genetically engineered *Escherichia coli*	Amperometric	9 nM	Gavrilaș et al. (2022)
Parathion	Genetically engineered *Escherichia coli*	Amperometric	10 nM	Gavrilaș et al. (2022)
Methylparathion	Genetically engineered *Escherichia coli*	Amperometric	15 nM	Gavrilaș et al. (2022)
Atrazine	*Anabaena variabilis*	Amperometric	0.07 µM	Aynalem and Muleta, (2021)
Lindane	Genetically engineered *Escherichia coli*	Electrochemical	2 ppt	Prathap et al. (2012)
Arsenite	Genetically engineered *Escherichia coli*	Optical	0.2 µg/l	Ramanathan et al. (1997)
Selenite	Genetically engineered *Escherichia coli*	Optical	5.8 ng/l	Gavrilaș et al. (2022)
Atrazine	*Anabaena variabilis*	Amperometric	0.07 µM	Tucci et al. (2019)
Diuron	*Chlamydomonas reinhardtii*	Chronoamperometric	0.2 µM	Gavrilaș (2022)

copper, silver, tin, mercury, and cobalt (Webster et al. 2014). The design and operation of the biosensor are portrayed in Fig. 7, and the various types of microbial biosensors used to detect environmental contaminants are shown in Table 3.

Ab-based biosensors (immunosensors)

The majority of glycoproteins that have the capacity to identify and entice antigens (pollutants) for binding are antibodies. These complexes are stable. Based on the transducing mechanism, immunosensors are categorized as electrochemical, which includes amperometric, potentiometric, and impedimetric, colorimetric, optical, and microgravimetric devices. It can also be separated into labelled and unlabelled sensors (Shin et al. 2012; Sagiroglu et al. 2011; Ramasubburayan et al. 2014; Roy et al. 2021; Kharkova et al. 2021; Melnikov et al. 2022; Kolahchi et al. 2018). The labelling contains a sensitive, observable pointing to the target bioreceptor. After analysis, the tag's activity was scaled. Tags can be made from various enzymes, fluorescent dyes, electroactive compounds, and nanoparticles. The formation of non-labelled immunosensors can be directly predicted by examining the physical changes the antigen–antibody complex results (Choi and Yoon 2023). The idea of unique interactions between antigen and antibody serves as the foundation for designing immunosensors. In electrochemical biosensors, antigen–antibody responses alter the electrical properties of the region between two electrodes (Grieshaber et al. 2008). Immobilizing antibodies on the surface of a solid matrix is one of the most crucial steps in the development of biosensors; yet, immobilization can occasionally cause a loss of function. Non-oriented immobilization is caused by random immobilization and steric hindrance brought on by a high antibody density (Kim et al. 2012; Zhang et al. 2017;

Table 4 Antibody-Based Biosensor to detect Environmental Contaminants

Contaminants	Developed biosensor	Bio recognition materials used	Sensing component	Detection limit	% of recovery	References
Atrazine	(Vol.) Biosensor	Monoclonal Ab used	AUNPs	0.016 ng mL^{-1}	95.5	Yang et al. (2015)
	FEET-based sensor	Monoclonal Ab used	Single wall carbon nanotube	0.01 ng mL^{-1}	87.3	Cao et al. (2009)
	Amp. sensor	Bacterial strained clonal Ab multipart	Magnetic beads functionalized using protein G	0.2 pg mL^{-1}	96–99	Cai et al. (2003)
Bacillus subtilis	Amp. sensor	Polyclonal Ab	AU Electrode with single wall CNT	10^{-2} CFU mL^{-1}	–	Mehne et al. (2013)
Microcystin	IMP	Antibodies	Graphene	50 pg mL^{-1}	–	Gavrilaș et al. (2022)

Mustafaoglu et al. 2015; Ocsoy et al. 2013; Nathan et al. 2012). Table 4 highlights the list of some of the available antibody-based biosensors.

Nanotechnology-based sensors

Recently, non-metallic nanomaterials including graphite, carbon nanotubes, and graphene as well as metallic nanoparticles like gold, copper, and silver have been used as biosensors. Utilizing nanomaterials broadens the binding surface area and improves surface accessibility. These biosensors' demonstrated great sensitivity and selectivity enable us to attain very low detection thresholds. The conductive ink-printed trips known as screen-printed electrodes (SPE) are printed on a substrate. This method adjusts a mould, stencil, or other net to serve ink into a substrate via a physical fence. After that, an insulator sheet is used to dry the printed ink and static. Examples of substrate materials include skin, plastics, ceramics, paper, and most recently, paper (Paimard et al. 2023). The redox reaction and its electrochemical significance serve as the foundation for the functioning principle of SPE sensors. The correct chemical alterations must be done in order to produce a superior sensing device, such as strengthening the electrode surface by increasing selectivity and adding new external area (Sailapu and Menon 2022). The best choice for expanding the electrode surface area is nanostructured components. Today, a variety of nanoscale materials, such as metallic nanoparticles, carbon-based nanomaterials like carbon nanotubes and graphene, carbon coatings, membranes, and a few conductive polymers, are used to develop electrode surfaces (Javaid et al. 2021). The fabrication method using screen-printing gives you the freedom to change the electrodes' morphology. Using SPEs improved by reduced graphene oxide and thionine (Roy et al. 2021) developed a new electrochemical enzyme biosensor to detect 3-hydroxybutyrate.

Conclusion and future perspectives

The goal of this review was to show how biosensors can answer the demand for quick, accurate, and dependable technology for detecting environmental pollutants. However, when applied to complex and irregular environmental samples with changeable compositions, these should be able to meet sensitivity and selectivity requirements. When developing biosensors for environmental pollutants detection, it is critical to consider mobility, cost, automation, and integration into professional devices, regardless of the sensing element or transducer. Continual use would necessitate rapid regeneration of biological activity during detection cycles. Most investigations use standardized laboratory samples to evaluate the biosensor's performance. Enzymes, aptamers, DNA, antibodies, and microorganisms are a few examples of biological sensing components. Despite difficulties with stability, potential interference, and ideal working circumstances, these components have the advantage of being amenable to enhancements in specificity and selectivity.

Recent study has shown that biomimetic sensors outperform enzyme-based biosensors in terms of kinetic performance. However, specificity and selectivity remain their main shortcomings. Although innovative nanocomposites and improved nanomaterials can be employed to produce environmental biosensors, in situ and real-time monitoring of toxins utilizing various methodologies has lately gained popularity. According to some daily news reports and a few scientific articles in the current literature, environmental monitoring has recently sparked interest in the use of drones, particularly in water and air quality monitoring, agricultural surveillance, and volcano gas measurements.

According to the biosensors evaluated in this review study, electrochemical and enzymatic biosensors are primarily employed for environmental monitoring. Enzymes have predominantly been used as recognition components in biosensors for pesticide detection due to their selectivity. However, enzymes are only helpful under specific circumstances due to their costly and time-consuming purification procedure, low thermal stability, and need for the ideal pH and temperature. Aptamers are a promising alternative for biosensor detection because to their versatility, denaturalization, and rehybridization, identification of targets with diverse functional groups, temperature stability, and in vivo synthesis. The use of immunosensors to identify substances such as endocrine disruptors and toxins has also been studied. Antibodies possessed good antigen specificity, but they also had problems with poor regeneration and difficult immobilization on sensor substrates. This requires research into the optimal settings for antibody formation and immobilization, which may take a long period and be detrimental to sensor development. As antibody activity declines, other antibody properties such as number, orientation, and position on the sensor surface may have an impact on sensor response and optimization.

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Declarations

Competing interests The authors declare no competing interests.

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