23 Biosensors for Environmental Health

Exploring the Biological and Socioeconomic Impacts

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23.1 INTRODUCTION TO BIOSENSORS

It is has been conclusively reported that various anthropogenic compounds are important for the release of various toxic pollutants into the environment. All over the world, environmental toxicants such as antibiotics, hazardous chemicals, insecticides and pesticides are released into the environment (Bilal et al., 2018). Although several procedures measure trace environmental pollutants through specialized techniques, undetected contaminants such as endocrine disruptors, pharmaceuticals, toxins and hormones need to be identified and quantified (Gaberlein et al., 2000). New prototypes urgently need to be developed to detect their existence in the environment. Low sample concentration, absence of sensitivity and lack of selectivity of traditional methods are among the major constraints of conventional methods. In addition, methods such as chromatography need long and specialized sample pre-treatment. From this perspective, biosensors are valuable tools to detect small sample sizes and minute concentrations of environmental pollutants (Arduini et al., 2017; El Harrad et al., 2018). The ability to design extremely accurate sites of recognition makes biosensors an appropriate alternative to conventional methods based on chromatography (Rodriguez et al., 2005). Biosensors has also been tested for detection and analysis of organic and inorganic environmental pollutants. Portability, on-site work, smaller size and ability to test pollutants in composite structures in minuscule sample preparations are the advantages provided by biosensors over traditional approaches for environmental implications. Many biosensors are specialized for a particular toxicant or may be used with a small range of pollutants (Roda et al., 2001; Rodriguez et al., 2006; Rogers, 2006).

Biosensors are typically categorized on the basis of bioreceptor factors such as whole cells (micro-organisms, plants, animals), DNA fragments and enzymes involved in the biological detection process, or on the basis of the physicochemical transducer used such as electrochemical, piezoelectric, optical or thermal. Microbes, antibodies, enzymes and DNA are the main types of bioreceptor component used in environmental pollutant analysis. It is also possible to develop these sensitive elements or biomaterials by applying genetic engineering techniques (Koedrith et al., 2014). In addition, the transducer and detector components work together according to different principles and convert the signal generated from communication of the analytes, i.e. biological sample materials, into a further signal which also can be quantified more easily. In general electrochemical transducer methods are applied in biosensors (Thevenot et al., 1999). The main component of the biosensor is the signal processor and it is mainly responsible for displaying results in a user-friendly manner.

The biosensor has three components: an organ of biological recognition material known as a bioreceptor, a transducer and a signal-processing mechanism (Sethi, 1994). Details of standard biosensors are shown in Figure 23.1. Further biosensors are grouped according to bioreceptor properties involved in the method of detection, such as whole cells (micro-organisms, plants, animals), DNA fragments and enzymes, or according to the physico-chemical character of transducers used

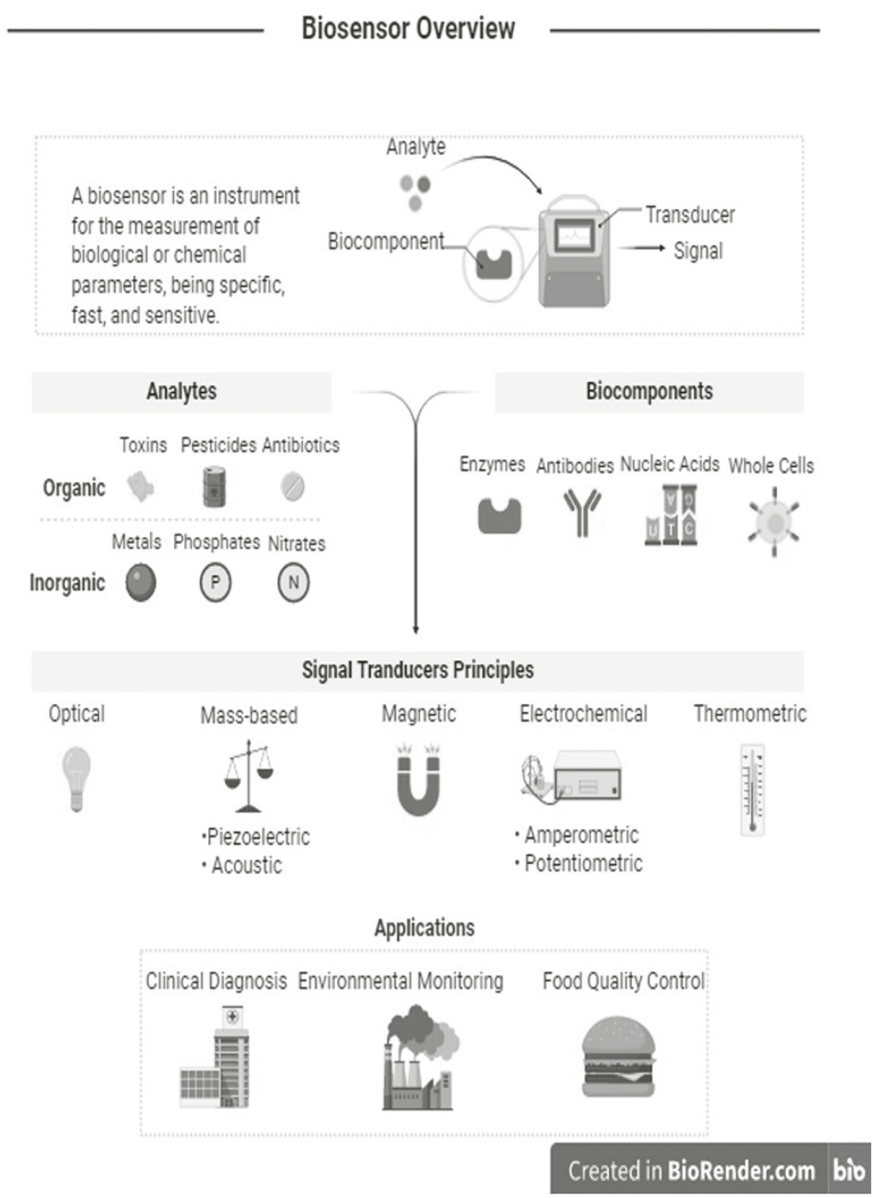

FIGURE 23.1 Potential biocomponents, signal transducers, principles and applications of biosensors.

for toxicant detection, such as electrochemical, piezoelectric, optical or thermal (Salgado et al., 2011; Wang et al., 2006). In biosensor manufacture, a key problem arises during the incorporation of biocomponents with the transducers on certain physical surfaces. The use of specific membranes with or without the addition of bifunctional agents has been well reported (Ikebukuro et al., 1996).

The most important tasks during design of a biosensor for analyte detection in a broad range of concentrations with no intervention depend on the selection of the correct bioreceptor molecule, a suitable immobilization method, selection of a precise transducer, and lastly the packaging in a compact shape. The biological material is fixed by traditional approaches, i.e. covalent or non-covalent, binding or membrane or physical entrapment. Contact is made between the biomaterial and transducer. The target of the analyte binds with the biomaterial that can be produced by an electrical reaction which can be calculated. The target analyte often changes the substance/product that could be correlated with the discharge of gas (oxygen), heat and ions. The transducer then transforms the product-associated changes of electric signals which can also be amplified, measured and displayed using the electronic system. The transducer translates the changes in association with the substance into electrical signals that can be amplified, analyzed and displayed by an electronic system. Several biosensors have also been developed using different combinations of bioreceptors and transducers. The biosensors used for environmental health monitoring mainly comprise various antibodies, enzymes, microbes and DNA as bioreceptors and various electrochemical transducers. Enzymes as biocatalysts can detect the presence of some analytes by calculating either the utilization or production of some chemical compounds such as CO_2, H^+, H_2O_2, NH_3 or O_2, and transducers therefore identify and detect the pollutants and associate their presence with the substrates (Verma and Singh, 2003).

23.2 CHARACTERISTICS OF AN IDEAL BIOSENSOR

1. Selectivity: Selectivity confirms that a certain analyte is detected by the sensor that does not react with the supplementary mixtures and contaminants. Selectivity is the key factor when selecting bioreceptors to create a biosensor and it is perhaps the most significant feature of any biosensor. Selectivity can best be defined by an antigen's interaction with various antibodies. Antibodies typically serve as bioreceptors which are immobilized on the transducer's surface. The antigen-containing solution is then exposed to the transducer, where antibodies only bind with antigens.
2. Signal stability: Stability is confined to the degree of susceptibility and the biosensing system to environmental disturbances. In the output signals of a biosensor under measurement, these disturbances can cause a drift. This can create an error in the calculated concentration and can also affect the detailed accuracy and precision of the biosensor. Stability is therefore the most important application for continuous monitoring and where long incubation details are necessary for a biosensor. The temperature-sensitive

response of electronics and transducers may affect the signal stability of a biosensor. Therefore, proper tuning of electronics is essential to ensure a constant sensor response. The affinity of the bioreceptor is another aspect that may affect stability; high-affinity bioreceptors enhance the strong electrostatic bonding application or the analyte's covalent linkage that strengthens the biosensor's stability.

3. Sensitivity (detection limit): This is the minimum analyte quantity (or concentration) that is detectable. The limit of detection or sensitivity is defined by the least number of analytes that can be quantified by a biosensor. In different environmental pollutant quality testing applications, to detect analyte concentration in the range of μg/ml or ng/ml, a biosensor is required to confirm the presence of different analyte traces in a sample. Sensitivity is therefore considered to be an important essential property of a biosensor.
4. Precision: This is the capacity of a biosensor to produce the same readings for repeated experimental set-ups under unchanged conditions. Changes of signals provide the detail inference which ensure the response of a biosensor has greater robustness and reliability.
5. Working range and regeneration time: This is the various ranges of concentrations of analytes at which the sensor can function, and the time needed to return the sensor to its working conditions after contact with the sample. The biosensor working range is characterized as the few changes in the analyte concentration that are needed to change the biosensor's response. Depending on the purpose, analyte concentration assessment over different working ranges is one of the main characteristics of a biosensor.

23.3 ENVIRONMENTAL APPLICATIONS OF BIOSENSORS

Various pollutants call for rapid and economic analytical tools and techniques to be used in comprehensive monitoring programs. Additionally, a few years ago, an increasing number of environmental pollution reduction policies and legislative measures were implemented in parallel with growing scientific and social interest (Rodriguez et al. 2004, 2005; Rogers, 2006; Rogers and Gerlach, 1996). The criteria for the application of most conventional analytical techniques studying environmental pollutants have been investigated; this often constitutes a major obstacle to their application on a daily basis. Recently the need for less time consuming and more ecofriendly techniques for environmental pollutant monitoring has been encouraged in implementing different formulations of technologies and more effective methodologies. From this perspective, biosensors appear to be a most suitable and effective alternative analytical tool.

Biosensors are a subgroup of chemical sensors that use a biological mechanism to detect analytes (Rodriguez et al., 2005; Rogers, 2006; Rogers and Gerlach, 1996). Biosensing process and techniques are being developed as effective tools for various applications, viz. agriculture, food quality analysis and in particular,

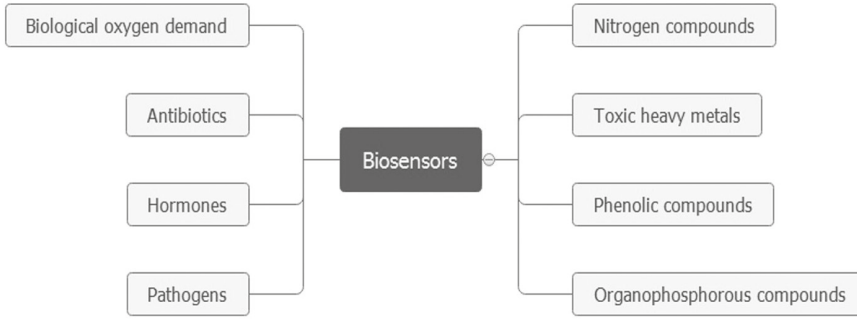

FIGURE 23.2 Different uses of biosensors for environmental pollutant monitoring and analysis.

environmental management and various sectors of medical applications. The key advantages provided by biosensors over traditional analytical techniques for environmental applications are miniaturization, portability, on-site work and the ability to evaluate pollutants in complex matrices with limited sample preparation.

The systems developed cannot yet compete, based on reproducibility and accuracy of analysis, with long-established analytical methods. However, regulatory authorities and industry can use them to provide adequate information for routine sample testing and screening (Rogers, 2006; Rogers and Gerlach, 1996; Sharpe, 2003). Biosensors also can be used as tools for environmental pollutant monitoring in the evaluation of environmental quality and for substance monitoring of organic and inorganic pollutants (Figure 23.2). In this chapter we present an overview of how the biosensor is useful for environmental monitoring, and describe various biosensors developed for various environmental applications, mainly air, water and soil quality monitoring and pathogen analysis.

23.4 GASEOUS POLLUTANT ANALYSIS AND AIR QUALITY MONITORING

There are various categories of air pollutants, including gases such as carbon monoxide, ammonia, chlorofluorocarbons, methane, sulfur dioxide and nitrous oxides, biological molecules and particulates like natural and inorganic products. Air pollutants can be produced by both natural processes and human interventions. Application of biosensors in air quality and gaseous pollutant monitoring has recently become an area of interest. Increased attention has been focused on in situ and real-time monitoring of pollutants, including the surveillance of agriculture, industrial waste and measurements of volcanic gases. For instance, in unmanned aerial vehicles and remotely piloted aircraft, a compact, sensitive and portable whole-cell biosensor has recently been incorporated (Phantom 2, Shenzhen, China) to monitor air and water quality and pollution in remote locations (Lu et al., 2015).

Air pollutants can be detected directly using biosensors, although the instruments developed for this purpose are very limited. Preliminary studies of environmental air pollutant monitoring were conducted for quantitative detection of volatile organic substances, such as methanol and formaldehyde using multiple-strain algal biosensors (Berno et al., 2004). In addition, the compound benzene has been analyzed and quantified in air samples by different biosensors (Lanyon et al., 2005).

23.5 SOIL AND WATER QUALITY MONITORING

Increasing numbers of potentially hazardous pollutants like chemical compounds, toxins and pathogens released to the soil and water bodies remain a critical global challenge (Salgado et al., 2011). In the soil and natural water bodies contamination of different toxic heavy metals and their subsequent ions poses significant hazards to human health, hence environmental safety is the most basic requirement for all living things on this earth. From this perspective, for the general protection and welfare of human beings, animals and plants, identification and control of environmental pollutants in the soil and water are essential.

23.6 TOXIC HEAVY-METAL ANALYSIS

Contamination by toxic heavy metals such as arsenic, lead, copper, zinc, cadmium and chromium is are one of the most hazardous soil and water pollutants even in trace amounts. It poses a severe risk to all living organisms, including to human health. Heavy metals are extensively present in polluted environments; for instance, many sites are substantially contaminated with chromium from tannery waste waters. In addition, fertilizers have become one of the contaminating sources of heavy metals. The heavy metals contained in chemical fertilizers can be harmful for human health as the crop will have heavy metals in its leaves and fruit (Atafar et al., 2010).

Existing approaches to detect various heavy metals include chromatographic spectroscopic, voltammetry methods that generally detect the species which could be at low concentrations or in single doses. These conventional techniques are typically costly and cannot easily be used for in situ analysis. Hence fast, compact and low-cost pollution analysis and monitoring tools are a global priority. Generally bacterial biosensors are applied for the recognition of toxic metals in soil and water samples, and their genes resistant to these target toxic metals are employed as bioreceptor molecules (Nigam and Shukla, 2015). Few bacterial species that have effective resistance against heavy metals have been assessed as potential biological receptors for the identification of zinc, copper, silver, tin, mercury, cobalt, etc. Some biosensors have also been evaluated by fusion of heavy genes that are resistant to different heavy metals with genes related to the expression of bioluminescent proteins, such as luciferin for the identification of elements present in soil and water samples. The detection of toxic heavy metal and its subsequent ion can

also be recognized by enzyme-catalyzed reactions, as several ions directly suppress the activity of enzymes at low concentrations (Verma and Singh, 2003).

For the detection of highly toxic and pervasive environmental pollutants like heavy metal ions, mercury ions (Hg^{2+}) have been used as representative targets for testing in DNA optical biosensors. It is fast, economical and portable for on-site quantitative detection of mercury in various water samples within a fraction of minutes. Chromium ions may be accumulated by plants cultivated in such fields. Recently, using single-stranded DNA and magnetic substrates, the surface enhancement Raman spectrum (SERS) biosensor was reported for the rapid and effective recognition of Hg^{2+} (Madianos et al., 2018; Yang et al., 2017). The two fluorescence-dependent optical biosensors were mainly designed to use DNA aptamers (Chen et al., 2017) and DNAzymes/carboxylated magnetic beads (Ravikumar et al., 2017) to detect Pb^{2+} in lake and pond water samples. For the detection of Pb^{2+} and Cd^{2+}using mesoporous carbon nitride/self-doped polyaniline nanofibers a multi-analyte biosensor has been suggested where the limits of detection were 0.2 and 0.7 nM (Zhang et al., 2016). Similar detection limits of 0.33 and 0.24 nM were obtained respectively for Pb^{2+} and Cd^{2+}, using a wireless biosensor based on magnetoelastic theory, which enables real-time monitoring in remote places (Guo et al., 2018). A modern electrochemical biosensor has been proposed to detect Zn, using paper-based, graphene chitosan and oxide microfluidic channels (Li et al., 2017). In complex environmental samples, the biosensor was capable of detecting Zn^{2+} because it was found to be selective when the other seven cations (Cu^{2+}, Fe^{3+}, Cd^{2+}, Hg^{2+}, Mn^{2+}, Mg^{2+} and Ag^{2+}) were examined (Li et al., 2017). For the identification of Cu^{2+} by fusion of a Cu^{2+} inducible promoter with the *lacZ* gene, a microbial recombinant biosensor of amperometric kind has been developed (Law and Higson, 2005).

23.7 BIOCHEMICAL OXYGEN DEMAND

Biochemical oxygen demand (BOD) is a significant parameter used to assess the biodegradable organic pollutant's concentration in a water sample. In routine practice, BOD determination of any sample is a time-consuming process, i.e. it takes 5 days, and as a result it is not suitable for rapid and online monitoring of water samples. In order to shorten the time required to quantify BOD in water samples and to provide rapid input on the state of water quality, BOD biosensors have been developed using recombinant *Escherichia coli* and *Photobacterium phosphoreum* as potential signal indicators of BOD in domestic wastewaters (Cheng et al., 2010). Recombinant *E. coli* cells with *Vibrio fisheri* gene lux AE-dependent biosensors were developed for the measurement of BOD by Nakamura and Karube (Simona et al. 2011). Furthermore Kwok et al. (2005) developed simultaneously multi-sample assessment of BOD testing of wastewater samples using an optical biosensor. Biosensors used for BOD analysis using yeast with an oxygen probe have recently been developed to analyze the various organic contaminants more rapidly than traditional ones.

23.8 PATHOGENIC ORGANISMS

The presence of pathogenic organisms in the matrices of the environment, especially in water chambers, may pose a serious risk for human beings, and recently biosensors have been reported to monitor pathogenic organisms in the environment. Methods generally used to identify pathogenic species are dependent on traditional colony culture techniques and antibody-dependent assays, polymerase chain reaction (PCR) techniques. Such techniques are laborious, time consuming and expensive. An easy and sensitive aptamer-dependent biosensor for the detection of a particular *E. coli* outer membrane was designed using two different aptamers. The technique has also been used for magnetic bead enhancement, and another has been used as a signal reporter particularly for *E. coli*, which was amplified by isothermal strand displacement and further recognized through a flow biosensor. The pathogen recognition limit is as low as 10 units of colony formation per milliliter (CFU mL^{-1}). This technique may also be applied to detect other bacterial species using multiple bacterium-specific aptamers (Wu et al., 2015).

For complex environmental water sample analysis rapid and precise optical biosensors based on surface plasmon resonance have been reported to detect the metabolically active *Legionella pneumophila* (Enrico et al., 2013; Foudeh et al. 2015). In one report, the detection principle was dependent on the identification of bacterial RNA by the immobilized RNA-sensing element probe on the gold surface of a biochip (Foudeh et al., 2015). In another experiment, *E. coli* has been found in underground water supplies by a whole-cell imprinting biosensor dependent on piezoelectric and optical principles, providing capabilities of real-time identification (Yilmaz et al., 2015). As a detection factor, a polymerizable type of histidine (N-methacryloyl-L-histidine methyl ester) was used and immobilized on gold surfaces, achieving close recognition to that of natural antibodies. An entire cell-dependent micro-contact-imprinted capacitive biosensor dependent on gold electrodes for the identification of *E. coli* was obtained with an enhanced detection limit (70 CFU mL^{-1}) in river water samples (Idil et al., 2016). Also, in air-borne dust, specifically during Asian dust events, the detection of pathogenic bacteria (*Bacillus subtilis*) was reported through an electrochemical immunosensor which is based on single-walled carbon nanotube (SWCNT)-gold electrodes (Yoo et al., 2017).

23.9 ANTIBIOTICS

The existence of antibiotics in soil and water is troubling because they promote antibiotic resistance of bacterial species (Coille et al., 2002). The extensive applications of antibiotics pose significant environmental issues as antibiotic resistance may be passed to humans when infected milk and meat products are consumed (Setford et al., 1999). Most biosensors are therefore intended for the determination of antibiotics in biological and food samples, although their use for monitoring soil and water samples should be considered. For instance,

the commercial biosensor BIACORE 3000 has been used to analyze the cross-reactivity of two sulfonamides: furosemide and sulfamethazine (Ahmad et al., 2002). The identified sulfamethazine has also been determined by Akkoyun et al. (2000) in animal urine with an optical immunobiosensor. In the development of three corresponding whole-cell biosensors, Hansen and Sorensen (2000) offered the choice of three distinct recombinant cells modified by a tetracycline-inducible promoter. Different biosensors are able to determine penicillin G (Setford et al., 1999) and tetracyclines (Hansen and Sorensen, 2000) in milk and food quality monitoring. In a review by Patel (2002), more reference to biosensors for the detection of antibiotic determination can also be found.

23.10 HORMONES

Owing to the rising population and more intensive farming, synthetic and natural hormone residues can be found in the soil and water as a result of human or animal excretion. Hormones like estradiol, ethinylestradiol and estrone have been detected at ng/L levels in water (Belfroid et al., 1999); some of these hormones may have endocrine-disrupting function in terrestrial and aquatic fauna even at these low concentrations. Estrone, progesterone and testosterone, along with the other organic pollutants, have also been determined with a fully automated optical immune biosensor in water samples, reaching limits of detection up to sub-ng/L (Hua et al., 2005; Rodriguez et al., 2004). In water samples, estrone, testosterone and progesterone, along with other organic contaminants, were determined by a fully automatic optical immune biosensor, exceeding detection limits up to sub-ng/L (Hua et al., 2005; Rodriguez et al., 2004).

23.11 PHENOLIC COMPOUNDS

Phenols and their derivatives are known to be poisonous substances and are present in various industrial effluents in which fibers, polymers, dyes, pharmaceuticals, pesticides, detergents and disinfectants are produced and synthesized (Rogers, 1995). These compounds have also been reported to exhibit significant toxic effects in plants and animals, causing mutagenicity and genotoxicity and reducing other biological processes and mechanisms, such as respiration, photosynthesis and enzyme-induced reactions at very low concentrations. Therefore, due to their high toxicity, phenols and their derivatives are defined as hazardous pollutants and are listed by the European Commission and the US Environmental Protection Agency as hazardous items and main pollutants.

Some significant enzymes such as laccase, peroxidase and tyrosinase, are exploited for the degradation of phenolic compounds and biosensor development. Toxic phenolic compounds in water usually interact with DNA. These interactions can be used in electrochemical DNA biosensors to generate a response signal. Based on this operation, a number of electrochemical DNA sensors for phenolic compound monitoring have been created. One of them is a disposable electrochemical

DNA biosensor made by immobilizing double-stranded DNA on to the surface of a disposable carbon screen-printed electrode. Amperometric biosensors with tyrosinase are immobilized in a hygrogel on a graphite electrode, which determines the phenol index in environmental samples. In addition, these organic pollutants can be oxidized by conventional carbonaceous electrodes generally at relatively high voltage (approximately 0.8 V).

Optical methods for determination of phenolic compounds have been developed in recent years. For example, chlorophenols can be detected with a chemiluminescence fiber-optic biosensor (Degiuli and Blum, 2000). Several phenol-detecting biosensors have been described using different micro-organisms either in immobilized form or in free state (Mehndiratta et al., 2013; Mulchandani et al., 1998; Theron and Cloete, 2002).

Cyanide is toxic to human health and inhibits the respiratory system by binding with cytochrome oxidase. *Saccharomyces cerevisiae* has been well reported as a potential microbe used as a sensor to analyze cyanide concentrations in water samples; the presence of cyanide inhibits the respiration process of yeast (Gavrilescu et al., 2015). Cyanide is very poisonous and by binding to cytochrome oxidase it suppresses respiration; *S. cerevisiae* has been developed as a microbial biosensor for tracking concentrations of cyanide in river water (Gavrilescu et al., 2015). An oxygen electrode that exploits immobilized bacteria has been developed to monitor the existence of cyanide (Attar et al., 2015; Lanyon et al., 2005).

23.12 NITROGEN COMPOUNDS

Nitrogen compounds, such as nitrite and nitrate, that are used to maintain the fertility of the soil, are the most ubiquitous chemical pollutants in soil and groundwater. They are not safe for living organisms, including in human health, since they irreversibly interfere with hemoglobin, inhibiting oxygen transport and causing methemoglobinemia, mutagenicity, carcinogenicity and blue-baby syndrome in infants. Thus, the intake of these ions in any form contributes to severe health complications. The high level of nitrate concentration in surface and groundwaters also damages aquatic environments. In accordance with this, measures have been enacted for municipal wastewater treatment to mitigate emissions, including nitrate pollution from domestic and commercial sewage of treatment plants (Rodriguez et al., 2005).

Over the past few decades, for determination of nitrate, spectrophotometric and ion exchange chromatography combined with spectrometric and conductometric approaches has been well reported (Cho et al., 2002). The majority of existing approaches used to detect nitrogen compounds include chromatographic spectroscopic, voltammetric methods that generally detect species at low concentrations. These conventional techniques are typically costly and not easy to use for in situ analysis. Hence fast, compact and low-cost pollution analysis and monitoring tools are a global priority.

A highly responsive, rapid and stable conductometric enzyme-dependent biosensor has been recorded for the detection of nitrate in water. An amperometric biosensor has been developed to evaluate nitrite by immobilizing cytochrome c nitrate reductase of *Desulfovibrio desulfuricans* and double-layered hydroxide containing anthraquinone-2-sulfonate (Chen et al., 2007). The reaction of the established sensor was rapid and the nitrite concentration was calculated in the 0.015–2.35 μmol range with a 4 nmol detection limit (Rogers, 1995). A disposable microbial sensor has been developed for the detection of urea in milk by combining an ammonium ion-selective electrode and urease enzyme-producing bacteria (Timur et al., 2004). For the detection of urea in milk, disposable microbial sensors have also been developed by combining an ammonium ion-selective electrode and urease enzyme-producing bacteria (Timur et al., 2004).

23.13 ORGANOPHOSPHORUS COMPOUNDS

Organophosphorus (OP) compounds are a kind of chemical substance commonly used in agriculture as insecticides to combat a variety of insect pests, carriers that spread diseases and weeds. For the evaluation of OPs in various samples enzyme-based biosensors have been evaluated on the basis of the inhibition of the particular enzyme by these OP compounds. Examples of biosensors for the recognition of carbamate pesticides and OPs, due to their inhibitory properties, include oncolin oxidase and acetyl cholinesterase (Andreou and Clonis, 2002; Andres and Narayanaswamy, 1997; Koedrith et al., 2014). Several biosensors were developed where pH electrode is connected with *E. coli* designed by recombinant DNA technology, and a wild-type OP-metabolizing bacterium of *Flavobacterium* sp. which induces the expression of the intracellular organophosphorus hydrolase on the cell surface (Espinosa-Urgel et al., 2015; Lehmann et al., 2000).

23.13.1 Pesticides

Of all the environmental toxins present in the atmosphere, plants, soil, water and food, pesticides are the most prevalent (Rodriguez et al., 2004). Owing to their broad scope of action pesticides (insecticides, herbicides and fungicides) are used all over the world. They are purposely introduced into the atmosphere and end up polluting it by different methods. The incidence of pesticide contaminants and metabolites in water, soil and fruit is among the largest problems and is a key concern (Mostafa, 2010). Pesticides are noticeable environmental pollutants because of their growing use in agriculture. The ongoing control of high pesticide levels in water, air and food has thus become a crucial practice for human health (Cesarino et al., 2012). Of all the pollutants in the environment pesticides are the most widespread and can be found in soil, water, air and plants. The European Community has imposed limits on concentration of pesticides in soil and water. The European Commission has also set residue thresholds for their use due to the toxicity of these pesticides and their existence in environmental samples. Conventional

chromatographic approaches, such as high-performance liquid chromatography (HPLC), are efficient in environmental pesticide analysis, but some limitations are correlated with restrictions that prohibit their usage. Development of biosensors for the direct recognition of pesticide is of special importance because of the limitations of traditional approaches. The greatest use of biosensors for detection of pesticides found enzymatic biosensors which inhibit the choice of enzyme. The degradation of the pesticide parathion by the microbial enzyme parathion hydrolase was used by an amperometric sensor to detect the presence of pesticide. In the presence of acetylcholine esterase, the same approach was used to detect acetylcholine by biocatalytic degradation. Nanoparticles based on iridium oxide have been used in enzyme biosensors with tyrosinase based on low-cost printed carbon film electrodes for the detection of chlorpyrifos in river water samples (Mayorga et al., 2014).

23.13.2 Herbicides

Herbicides are mainly used to kill specific unwanted herbs and small plants, leaving the desired crop unharmed. There are reports on widely varying toxicity and possible carcinogenicity. Some herbicides have negative impacts on bird populations, although these can vary widely. Likewise, biosensors in which amperometric and optical transducers are used can detect herbicides (phenyl urea) and triazines which inhibit photosynthesis (Karube and Nakaniki, 1994). Biosensors have been developed for the recognition of herbicides, viz. triazines and phenyl ureas, which prevent photosynthesis through receptors of the membrane of chloroplasts, thylakoid or whole cell, such as single-cell algae, for which primarily optical transducers and amperometric biosensors are used (Cock et al., 2009); these inhibit photosynthesis. Photosynthesis process inhibition is an indicator that rapidly reflects the toxic effect of pollutants. Based on this feature, some biosensors have been developed to detect herbicides in the environment, such as phenylurea and triazines. The principle of operation of these sensors is based on water plastoquinone oxidoreductase (photosystem II). Amperometric biosensors have exhibited selective sensitivity to phenylurea and triazine herbicides (Jose et al., 2003).

23.13.3 Insecticides

Dichlorvos (2,2-dichlorovinyl dimethyl phosphate, generally abbreviated as a DDVP) is an organophosphate broadly used as an insecticide to combat domestic pests and to protect stored goods from insects. For the recognition of dichlorvos in fruit samples, simple and fast fluorescence biosensors using a quantum dots method, bi-enzyme (acetylcholinesterase and choline oxidase) and acetylcholine as substrate have been suggested (Meng et al., 2013). Another enzymatic biosensor based on acetylcholinesterase–zinc oxide-modified platinum electrode was generated for the identification of dichlorvos with a 12 pM detection limit in orange samples (Sundarmurugasan et al., 2016). For the identification of carbamate insecticides

(carbofuran), an electrochemical biosensor dependent on acetylcholinesterase immobilized on iron oxide-chitosan nanocomposite was used (Jeyapragasam and Saraswathi, 2014).

23.14 CHALLENGES IN BIOSENSOR RESEARCH FOR ENVIRONMENTAL MONITORING

Biosensors have been used for about 50 years, and the over the past 20 years research in this field has made tremendous contributions towards environmental health monitoring. However, in this field, despite numerous advances in biosensor development, relatively few biosensors have achieved global commercial growth at retail level for accurate, rapid and on-site monitoring of environmental pollutants. For the large-scale production of robust, sensitive and reliable biosensor devices with good specificity, it is a significant challenge to engage researchers from chemical, physical, biological and computer disciplines to work together. In addition, difficulties in transforming academic research into commercially feasible prototypes, complex regulatory systems in engineering of biological organisms and biomaterial are other challenges. Many elements of biosensors are composed of non-material; hence their exposure into the environment and accumulation in human beings through the agri-food chain are possible. The development of biosensors for on-site air pollutants and biological allergens or pathogen monitoring in air samples represents a challenge in environmental health analysis, where selectivity and specificity must be the main parameters to be controlled and optimized. Moreover, existing biosensors have a limited life expectancy, and due to the sensitive nature of biological material used in biosensor systems, they cannot tolerate adverse environmental conditions.

23.15 CONCLUSION

The environment is continuously burdened by the release of a number of toxic pollutants through anthropogenic activities that damage various ecological parameters; thus the integrity of various ecological system is under threat. The prevalence of these toxic pollutants is now a universal threat to protection of the environment and living beings. Presently, a large spectrum of biosensors such as aptasensors, electrochemical biosensors, enzymatic biosensors and immunosensors have been designed and utilized for various ecological quality as well as quantity monitoring devices in the evaluation of different harmful chemicals, or biological pollutants.

The use of novel and advanced biotechnological approaches such as recombinant-DNA technology and enzyme engineering has accelerated the efficacy of recognition factors and promoted biosensor research and development for future environmental applications. In addition, various computational biology approaches may be applied to program potential microbes for their enhancement of precision, accuracy and selectivity of biosensors, so that particular toxicity produced by

various forms of pollutant may be sensed. Therefore, the use of biosensors has immense potential for the recognition and detection of toxic pollutants and ecological scrutiny in the environment.

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