VIEW POINTS
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Biosensors for the Detection of Environmental and Urban Pollutions

Nasser Hashemi Goradel,[1,2] Hamed Mirzaei,[3] Amirhossein Sahebkar,[4] Mohsen Poursadeghiyan,[5] Aria Masoudifar,[6] Ziba Veisi Malekshahi,[1] and Babak Negahdari [1]*

[1]*Department of Medical Biotechnology, School of Advanced Technologies in Medicine, Tehran University of Medical Sciences, Tehran, Iran*

[2]*Tehran Urban Planning and Research Center, Tehran, Iran*

[3]*Department of Medical Biotechnology, School of Medicine, Mashhad University of Medical Sciences, Mashhad, Iran*

[4]*Mashhad University of Medical Sciences, Biotechnology Research Center, Mashhad, Iran*

[5]*Research Center in Emergency and Disaster Health, University of Social Welfare and Rehabilitation Sciences, Tehran, Iran*

[6]*Department of Molecular Biotechnology, Cell Science Research Center, Royan Institute for Biotechnology, ACECR, Isfahan, Iran*

ABSTRACT

Release of harmful pollutants such as heavy metals, pesticides, and pharmaceuticals to the environment is a global concern. Rapid and reproducible detection of these pollutants is thus necessary. Biosensors are the sensitive and high specific tools for detection of environmental pollutants. Broad range various types of biosensors have been fabricated for this purpose. This review focuses on the feature and application of biosensors developed for environmental and urban pollutants detection. J. Cell. Biochem. 119: 207–212, 2018.

KEY WORDS: HEAVY METALS; PESTICIDES; BIOSENSOR; ENVIRONMENTAL POLLUTANTS

One of the consequences of rapid human and technological advances is extensive man-made chemicals and by-products made in industries or combustion processes. These deleterious pollutants are increasingly released in the environment and affect the quality of the environment. Environmental pollution is the major source of the mankind health problems and imposes unfavorable socioeconomic sequels [Koedrith et al., 2015]. Pesticides, heavy metals, pharmaceuticals, and water-borne pathogens are major culprits for environmental and urban pollution. Thus, there is an increasing need for effective tools to detect these toxicants and estimate the related risks associated with the release of large quantities of environmental pollutants. Although traditional approaches have enabled accurate analysis of chemical or physical properties of environmental samples [Nigam and Shukla, 2015], there is still need to fast and cost-effective tools for the detection and monitoring of toxic pollutants [Palchetti and Mascini, 2008].

Biosensor is known as one of powerful tools for the detection of environmental and urban pollutions. IUPAC definition form a biosensor is "as a self-contained integrated device that is capable of providing specific quantitative or semi-quantitative analytical information using a biological recognition element (biochemical receptor), which is retained in direct spatial contact with a transduction element" [Palchetti and Mascini, 2008; Vogrinc et al., 2015]. Indeed, biosensor is a device which converts a biological or biochemical signal into a measurable electrical signal [Ezeonu et al., 2012] and they are valuable tools for the detection of chemical and harmful substances in health-care products, foods, and the environmental [Rebollar-Pérez et al., 2015]. Biosensors can be used for continuous monitoring of a contaminated area. They may also offer advantageous analytical features, such as high specificity and sensitivity. At the same time, biosensors offer the possibility of determining not only specific chemicals, but also their biological

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Correspondence to: Babak Negahdari, Department of Medical Biotechnology, School of Advanced Technologies in Medicine, Tehran University of Medical Sciences, Tehran, Iran. E-mail: negahdari_md@yahoo.com

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effects, such as toxicity, cytotoxicity, genotoxicity, or endocrine disrupting effects [Rodriguez-Mozaz et al., 2006]. In comparison with traditional techniques, biosensors have several advantages including portability, miniaturization, capacity of pollutant detection in complex matrices with minimal sample preparation [Rodriguez-Mozaz et al., 2006; Palchetti and Mascini, 2008], and rapidity and reliability of detection [Saleem, 2013]. In addition, the use of conventional methods usually requires skilled personnel to operate as a technician [Saleem, 2013] and specialized laboratories [Nigam and Shukla, 2015]. Here, we present a brief review of the biosensor classes and their applications in the monitoring of environmental pollutions.

BIOSENSORS AND THEIR CLASSIFICATION

According to the IUPAC definition, there are three basic components in a biosensor: a biological recognition element, a transducer, and a signal processing system [Nigam and Shukla, 2015]. Recognition of the target analyte is made by a bioreceptor which is a biomolecule, and transducer converts the recognition event into a measurable signal [Koedrith et al., 2015]. Figure 1 shows a schematic representation of a biosensor.

On the basis of the bio-recognition principles or signal transduction, biosensors are classified into various categories [Rebollar-Pérez et al., 2015]. According to the transducing component, biosensors are designed as electrochemical (amperometric, chronoamperometric, potentiometric, conductometric, capacitative, field-effect transistors), optical (absorbance, reflectance, luminescence, chemiluminescence, bioluminescence, fluorescence, refractive index, light scattering), piezoelectric (mass sensitive quartz crystal microbalance), or thermal (thermistor, pyroelectric) [Ezeonu et al., 2012].

Electrochemical. Low cost, ease of use, and construction simplicity are the advantages of electrochemical biosensors [Ronkainen et al., 2010]. Electrochemical biosensors measure the electrical properties of biological systems. Although variety of recognition systems are used in the design of biosensors, electrochemical biosensors predominantly involve enzymes [D'Orazio, 2003]. In the design of electrochemical biosensors, three electrodes are used: reference electrode (usually Ag/AgCl) for maintaining stable potential, counter, or auxiliary electrode for establishing a connection to the electrolytic solution, and working electrode. In the amperometric, potentiometric, and conductometric biosensors current, potential or charge accumulation and conductive properties of the medium are measured, respectively [Grieshaber et al., 2008]. Impedimetric biosensors measure resistance and reactance, where current measurement as a result of a potentiometric effect at a gate electrode is the field-effect biosensors mechanism [Guiseppi-Elie and Lingerfelt, 2005].

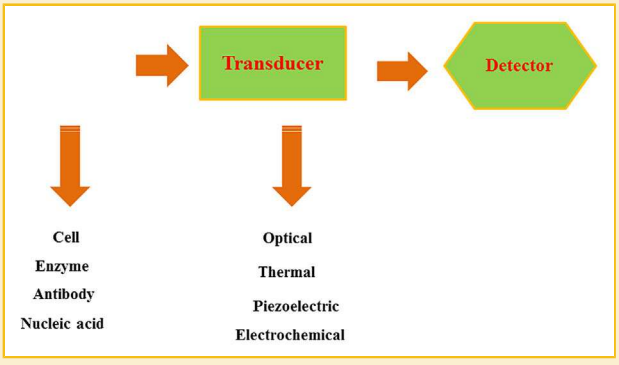

Fig. 1. Schematic components of a biosensor.

Optical. Using an optical transducer in order to detect optical properties changes is the design principle of optical biosensors [Eltzov et al., 2011]. Adsorption, fluorescence, luminescence, and refractive index are the most commonly used properties of the optical biosensors [Dai and Choi, 2013]. Optical biosensors employ electromagnetic waves for detecting analyte and could immobilize bio-element interactions which are known by the name of surface plasmon resonance (SPR) [Monošík et al., 2012]. SPR employs change in the refractive index of surface metal for detection [Patel et al., 2010].

Piezoelectric. Piezoelectric biosensors are sensitive to changes in mass, density, or viscosity of samples in contact with its active surface. The relationship between the resonant frequency of an oscillating piezoelectric crystal and the mass deposited/adsorbed on the crystal surface is the theoretical principle of piezoelectric biosensors (Kumar, 2000; Marrazza, 2014). Quartz crystal microbalance (QCM) is the most well-known piezoelectric biosensor that has a thin plate of quartz, with metallic electrodes (usually gold) attached to each side of the plate [Marrazza, 2014]. In QCM, the bioreceptor is immobilized on quartz crystal and a constant flow of analyte is applied to the immobilized ligand in order to facilitate the reaction between bioreceptor and analyte. In the end, sensogram determines viscosity changes as a signal [Jia et al., 2013]. Because of bioreceptor immobilization and loosing degree of freedom, true affinities measurement of QCM does not happen [Marrazza, 2014].

Thermal. Quantification of the release or absorbance of thermal energy during a biochemical reaction is the principle of these biosensors [Monošík et al., 2012]. Since thermal activity is one of the essential parts of biochemical reactions, thermal biosensing is a broadly applicable method (Wang et al., 2008).

Biosensors can utilize biological molecules (antibody, enzyme, nucleic acid), living biological systems (cell, tissue, or whole organ) or biomimetic materials for detection and recognition [Koedrith et al., 2015]. Thus, according to the biorecognition method, biosensors can be classified as:

(1) Enzyme based biosensors: specificity, availability, and variety of functions makes enzymes appropriate to be employed as recognition elements. According to the mode of analyte monitoring, enzyme-based biosensors are classified into direct and indirect modes. Monitoring of analyte concentration or formed products during enzymatic reactions is called direct mode and monitoring of enzyme inhibition by the analyte is called indirect mode. In the enzyme-based biosensors, indirect mode is more favorable [Rebollar-Pérez et al., 2015]. Immobilization of enzyme on the solid surface is one of the most important aspects of biosensor design. Covalent binding, entrapment, and microencapsulation are the most common

TABLE I. Biosensors for Detection of Organic and Inorganic Pollutants

Target	Transducer	Bio-element	Reference
Zinc, Cadmium	Optical	Microorganism (*E.coli*)	Vogrinc et al. [2015]
Glyphosate	Electrochemical	Enzyme (*atemoya peroxidase*)	Oliveira et al. [2012]
Bisphenol A	Optical	Antibody	Rodriguez-Mozaz et al. [2005]
Copper	Electrochemical	Enzyme (HRP)	Moyo et al. [2014]
Methyl Parathion	Optical	Microorganism (*Flavobacterium*)	Vogrinc et al. [2015]
Aflatoxin	Electrochemical	DNA	Marrazza et al. [1999]
Atrazine, Carbofuran	Piezoelectric	Antibody	Jia et al. [2013]
Copper	Optical	Microorganism (yeast)	Vopálenská et al. [2015]
Catechol	Electrochemical	Microorganism (*Lactobacillus*)	Vogrinc et al. [2015]
Nonylphenol	Electrochemical	Antibody	Evtugyn et al. [2006]
Nitrate	Optical	Microorganism (*E. coli*)	Taylor et al. [2004]
Parathion	Piezoelectric	Antibody	Funari et al. [2013]
Mercury	Optical	DNA	Knecht and Sethi [2009]
p-Nitrophenol	Electrochemical	Microorganism (*Pseudomonas*)	Banik et al. [2008]
Arsenite, Selenite	Optical	Microorganism (*E. coli*)	Ooi et al. [2015]
Chlorophenol	Electrochemical	Enzyme (HRP)	Qiu et al. [2013]
Salicylate	Optical	Microorganism (*E. coli*)	Shin [2010]
Paraoxon, Carbofuran	Electrochemical	Enzyme (AChE)	Bachmann and Schmid [1999]
Carbaryl	Piezoelectric	Antibody	Wang et al. [2014]
Serotonin	Optical	Microorganism (yeast)	Nakamura et al. [2015]

immobilization methods. Immobilized enzyme-based biosensors advantages are less sample requirement, rapid analysis, and reduction of interference by the differential mode of operation in comparison with free enzyme-based biosensors [Turdean, 2011]. In most of the biosensors, glucose oxidase (GOx), horseradish peroxidase (HRP), and alkaline phosphatase are used as the enzyme component [Cao et al., 2011; Bănică, 2012]. As mentioned, enzyme inhibition (indirect) mode of biosensors is applied for monitoring of a wide range of environmental pollutants. In order to evaluate analyte concentration, percentage of inhibited enzymes after exposure to the inhibitor is measured [Rebollar-Pérez et al., 2015]. The pitfall of indirect mode biosensors for the detection of environmental pollutants is that few enzymes are sensitive to heavy metals [Turdean, 2011].

(2) DNA based biosensors: binding to a broad range of molecules with high affinity and specificity together with the catalytic activity of DNA molecules make DNA as a valuable option for designing biosensors [Palchetti and Mascini, 2008]. In biosensors, DNA can be used either in the native (Calf thymus, double-strand DNA as ds-DNA) or modified (single-strand DNA [ss-DNA]) form for the detection of DNA fragments, biological or chemical species [Turdean, 2011]. Principle of DNA-based biosensing is based on the highly specific hybridization of complementary strands of DNA. DNA-based biosensors are classified into two groups: affinity-based (genosensors and aptasensors) and catalytic-based (DNAzymes and aptazymes). In genosensors, hybridization of a probe (usually a short synthetic and sequence-specific oligonucleotide) and a signal transducer is the principal formation of biosensor. The most important factor for the construction of genosensor is probe selection and immobilization. In aptasensors, selected DNA plays the role of a highly specific receptor of biological or chemical species [Hianik and Wang, 2009]. Catalytic capability of DNA opens new category of biosensors by the name of DNAzymes. DNAzymes are isolated by in vitro selection are not been found in nature. Combination of DNAzymes which are able to make chemical modification on nucleic acids and aptamers which are able to bind to a broad range of molecules, generates aptazymes [Palchetti and Mascini, 2008].

(3) Ab-based biosensors (immunosensors): specific interactions between antigen and antibody is the principle in designing immunosensors [North, 1985; Long et al., 2013]. In electrochemical biosensors, changes in the electrical properties in the gap between two electrodes results from antigen-antibody reactions [Katz and Willner, 2003]. Immobilization of antibodies on the surface is one of the most critical steps in designing biosensors which can even cause loss of their function in case of non-oriented immobilization. Non-oriented immobilization results from random immobilization and steric hindrance due to high density of antibodies [Karyakin et al., 2000; Grieshaber et al., 2008].

(4) Whole cell-based biosensors: whole cells have been used as a biorecognition part in biosensors via immobilizing the cells on a transducer electrode [Ziegler, 2000]. In comparison with isolated enzymes, whole cells provide a better source of enzymatic activity especially for expensive or non-commercially available enzymes [Wang, 2006]. A microbial biosensor is a biosensor in which a microbe is immobilized on a transducer to monitor biochemical processes [Ronkainen et al., 2010]. Although using enzymes in the microbes is

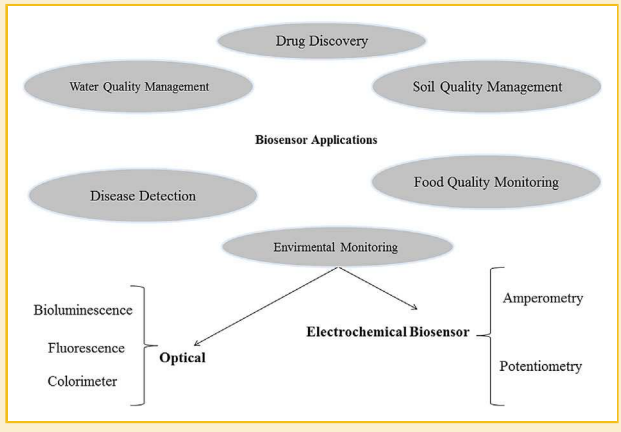

Fig 2. Various applications of biosensors.

time- and cost-effective [Dai and Choi, 2013], longer recovery times, longer response time, and hysteresis effect are disadvantages of microbial biosensors [Ronkainen et al., 2010]. Yeast biosensors are another type of whole cell-based biosensors which are highly specific for some targets [Jarque et al., 2016].

ENVIRONMENTAL MONITORING

As mentioned, environmental pollutants are harmful to human health. Generally, environmental pollutants are classified into two groups: organic compounds and inorganic compounds. Pesticides, hormones, polychlorinated biphenyls, dioxins, phenols, bisphenol A, surfactants, linear alkylbenzene sulfonates, alkanes, polycyclic aromatic hydrocarbons, antibiotics, and toxins are organic pollutants. Inorganic pollutants include metals, inorganic phosphates, and nitrate [Marrazza, 2014]. Table I shows some environmental pollutants and their respective biosensor detection systems. In the following sections, we discuss three dangerous types of pollutants. Figure 2 shows a range of Environmental applications of biosensors.

Pesticides. Because of exhaustive use in agriculture to increase productivity and crop yields, pesticides are ubiquitously present in the environment [Verma and Bhardwaj, 2015]. Pesticides cause nerve system disorders, immunological, and respiratory diseases, and are also carcinogenic [Sassolas et al., 2012]. Pesticides classification is based on their chemical structure: organochlorine (Atrazine), organophosphate (Parathion), carbamate, synthetic pyrethroides, and inorganic pesticides [Verma and Bhardwaj, 2015]. Organochlorine pesticides adversely alter reproductive system of fishes and could thus affect ecosystem [Vigneshvar et al., 2016]. The most widespread used biosensors for the detection of pesticides are enzyme-based biosensors that are especially based on the inhibition of acetyl cholinesterase (AChE) and colin oxidase [Rebollar-Pérez et al., 2015]. Inhibition of AChE in nerves result in the accumulation of the neurotransmitter acetylcholine which is life-threating [Verma and Bhardwaj, 2015]. Measurement of enzyme inhibition and components involved in the enzymatic reactions are used for the detection of pesticides [Sassolas et al., 2012].

Heavy metals. Heavy metals content is increased by mining and other industrial activities. Heavy metals are not degradable and accumulate in the environment over time. Almost all of heavy metals have toxic effects mediated by producing reactive oxygen species (ROS) [Gutiérrez et al., 2015]. Although some metals are needed for different biological processes [Rebollar-Pérez et al., 2015] such as enzymatic reactions (as a cofactor) [Ezeonu et al., 2012], they can induce enzyme inhibition in some cases [Rodriguez-Mozaz et al., 2006]. Thus, activation or inhibition of enzymes is used for designing heavy metal biosensors. Zinc and copper can be detected by the activation of alkaline phosphatase and ascorbate oxidase-based biosensors, respectively [Satoh and Iijima, 1995]. Glucose oxidase (GO) inhibition can be applied as a biosensor for the detection of heavy metals such as cadmium, cobalt, copper, and nickel [Ghica et al., 2013]. Optical biosensors for the detection of metals are based on the activity a reporter gene under the control of an inducible promoter [Rodriguez-Mozaz et al., 2006]. In this strategy that is called "turn on assay," the reporter signal level increases according to the pollutant concentration. β-galactosidase (*lacZ*), luciferase (*luc*), and green fluorescent protein (GFP) are the most popular reporter genes used in biosensor systems [Gutiérrez et al., 2015].

Pharmaceuticals. One of the current concerns about water contamination is improper excretion of hospital wastes. Commonly founded pharmaceuticals in the water are likes of antihypertensive drugs, beta-blockers, analgesics/anti-inflammatories, antibiotics, and psychiatric drugs. Therefore, detection of these compounds is essential to prevent life-threating effects on human and other living organisms. Enzyme-based biosensors using peroxidases, laccases, and tyrosinases are main biosensors for the detection of pharmaceuticals [Rebollar-Pérez et al., 2015]. Levetiracetam, an antiepileptic drug, can be detected using HRP-based biosensors [Alonso-Lomillo et al., 2009]. Another example is the laccase enzyme used for the detection of methyldopa which is an antihypertensive drug [Moccelini et al., 2011].

CONCLUSION

In this review, we summarized different biosensor types and their application in the environmental pollutant detection. Developing sensitive, specific, and cost-effective biosensors is crucial for the detection of small molecules. Another critical step in designing a biosensor is immobilization of biomolecules on the surface. In recent years, nanotechnology has found more important roles in the design and application of biosensors. Selection of materials and response to parameters such as pH and temperature are key steps for designing and optimizing sensing systems [Bidmanova et al., 2016]. The using of 3D micro-environment could help to encapsulation of whole cell especially transparent materials in the optical methods which will improve biosensor fields [Vigneshvar et al., 2016]. Well features of carbon nanotubes and graphene could make them as structures potential candidates for free labeling of biosensors [Ramnani et al., 2016].

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REFERENCES

Alonso-Lomillo MA, Domínguez-Renedo O, Hernández-Martín A, Arcos-Martínez MJ. 2009. Horseradish peroxidase covalent grafting onto screen-printed carbon electrodes for levetiracetam chronoamperometric determination. Anal Biochem 395(1):86–90.

Bachmann TT, Schmid RD. 1999. A disposable multielectrode biosensor for rapid simultaneous detection of the insecticides paraoxon and carbofuran at high resolution. Anal Chim Acta 401(1):195–103.

Bănică FG. 2012. Enzymes and enzymatic sensors. In: Chemical sensors and biosensors: Fundamentals and applications. Chichester, UK: John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118354162.ch3

Banik R, Prakash R, Upadhyay S. 2008. Microbial biosensor based on whole cell of *Pseudomonas sp.* for online measurement of p-nitrophenol. Sens Actuators B Chem 131(1):295–300.

Bidmanova S, Kotlanova M, Rataj T, Damborsky J, Trtilek M, Prokop Z. 2016. Fluorescence-based biosensor for monitoring of environmental pollutants: From concept to field application. Biosens Bioelectron 84:97–105.

Cao S, Chen J, Jin X, Wu W, Zhao Z. 2011. Enzyme-based biosensors: Synthesis and applications. In: Li S, Singh J, Li H, and Banerjee IA, editors. Biosensor Nanomaterials. Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany. https/doi.org/10.1002/9783527635160.ch5

D'Orazio P. 2003. Biosensors in clinical chemistry. Clin Chim Acta 334(1):41–69.

Dai C, Choi S. 2013. Technology and applications of microbial biosensor. Open J Appl Biosens 2:83–93.

Eltzov E, Pavluchkov V, Burstin M, Marks RS. 2011. Creation of a fiber optic based biosensor for air toxicity monitoring. Sens Actuators B Chem 155(2):859–867.

Evtugyn G, Eremin S, Shaljamova R, Ismagilova A, Budnikov H. 2006. Amperometric immunosensor for nonylphenol determination based on peroxidase indicating reaction. Biosens Bioelectron 22(1):56–62.

Ezeonu CS, Tagbo R, Anike EN, Oje OA, Onwurah IN. 2012. Biotechnological tools for environmental sustainability: Prospects and challenges for environments in Nigeria—a standard review. Biotechnol Res Int 2012:26. Article ID 450802. https://doi.org/10.1155/2012/450802

Funari R, Della Ventura B, Schiavo L, Esposito R, Altucci C, Velotta R. 2013. Detection of parathion pesticide by quartz crystal microbalance functionalized with uv-activated antibodies. Analyt Chem 85(13):6392–6397.

Ghica ME, Carvalho RC, Amine A, Brett CM. 2013. Glucose oxidase enzyme inhibition sensors for heavy metals at carbon film electrodes modified with cobalt or copper hexacyanoferrate. Sens Actuators B Chem 178:270–278.

Grieshaber D, MacKenzie R, Voeroes J, Reimhult E. 2008. Electrochemical biosensors-sensor principles and architectures. Sensors 8(3):1400–1458.

Guiseppi-Elie A, Lingerfelt L. 2005. Impedimetric detection of dna hybridization: Towards near-patient DNA diagnostics. Immobilisation of DNA on chips I. Top Curr Chem 260:161–186.

Gutiérrez JC, Amaro F, Martín-González A. 2015. Heavy metal whole-cell biosensors using eukaryotic microorganisms: An updated critical review. Front Microbiol 6:48.

Hianik T, Wang J. 2009. Electrochemical aptasensors-recent achievements and perspectives. Electroanalysis 21(11):1223–1235.

Jarque S, Bittner M, Blaha L, Hilscherova K. 2016. Yeast biosensors for detection of environmental pollutants: Current state and limitations. Trends Biotechnol. 34(5):408–419.

Jia K, Adam P-M, Ionescu RE. 2013. Sequential acoustic detection of atrazine herbicide and carbofuran insecticide using a single micro-structured gold quartz crystal microbalance. Sens Actuators B Chem 188:400–404.

Karyakin AA, Presnova GV, Rubtsova MY, Egorov AM. 2000. Oriented immobilization of antibodies onto the gold surfaces via their native thiol groups. Anal Chem 72(16):3805–3811.

Katz E, Willner I. 2003. Probing biomolecular interactions at conductive and semiconductive surfaces by impedance spectroscopy: Routes to impedimetric immunosensors, DNA-sensors, and enzyme biosensors. Electroanalysis 15(11):913–947.

Knecht MR, Sethi M. 2009. Bio-inspired colorimetric detection of Hg2+ and Pb2+ heavy metal ions using Au nanoparticles. Anal Bioanal Chem 394(1):33–46.

Koedrith P, Thasiphu T, Weon J-I, Boonprasert R, Tuitemwong K, Tuitemwong P. 2015. Recent trends in rapid environmental monitoring of pathogens and toxicants: Potential of nanoparticle-based biosensor and applications. Sci World J 2015:12. Article ID 510982. https://doi.org/10.1155/2015/510982

Kumar A. 2000. Biosensors based on piezoelectric crystal detectors: Theory and application. JOM-e 52(10):1–6.

Long F, Zhu A, Shi H. 2013. Recent advances in optical biosensors for environmental monitoring and early warning. Sensors 13(10):13928–13948.

Marrazza G. 2014. Piezoelectric biosensors for organophosphate and carbamate pesticides: A review. Biosensors 4(3):301–317.

Marrazza G, Chianella I, Mascini M. 1999. Disposable DNA electrochemical biosensors for environmental monitoring. Anal Chim Acta 387(3): 297–307.

Moccelini SK, Franzoi AC, Vieira IC, Dupont J, Scheeren CW. 2011. A novel support for laccase immobilization: Cellulose acetate modified with ionic liquid and application in biosensor for methyldopa detection. Biosens Bioelectron 26(8):3549–3554.

Monošík R, Streďanský M, Šturdík E. 2012. Biosensors-classification, characterization and new trends. Acta Chimica Slovaca 5(1):109–120.

Moyo M, Okonkwo JO, Agyei NM. 2014. An amperometric biosensor based on horseradish peroxidase immobilized onto maize tassel-multi-walled carbon nanotubes modified glassy carbon electrode for determination of heavy metal ions in aqueous solution. Enzyme Microb Technol 56:28–34.

Nakamura Y, Ishii J, Kondo A. 2015. Applications of yeast-based signaling sensor for characterization of antagonist and analysis of site-directed mutants of the human serotonin 1A receptor. Biotechnol Bioeng 112(9):1906–1915.

Nigam VK, Shukla P. 2015. Enzyme based biosensors for detection of environmental pollutants-A review. J Microbiol Biotechnol 25(11): 1773–1781.

North JR. 1985. Immunosensors: Antibody-based biosensors. Trends Biotechnol 3(7):180–186.

Oliveira GC, Moccelini SK, Castilho M, Terezo AJ, Possavatz J, Magalhães MR, Dores EF. 2012. Biosensor based on atemoya peroxidase immobilised on modified nanoclay for glyphosate biomonitoring. Talanta 98:130–136.

Ooi L, Heng LY, Mori IC. 2015. A high-throughput oxidative stress biosensor based on Escherichia coli roGFP2 cells immobilized in a k-carrageenan matrix. Sensors 15(2):2354–2368.

Palchetti I, Mascini M. 2008. Nucleic acid biosensors for environmental pollution monitoring. Analyst 133(7):846–854.

Patel P, Mishra V, Mandloi A. 2010. Optical biosensors: Fundamentals & trends. J Engineer Res Stud 1:15–34.

Qiu C, Chen T, Wang X, Li Y, Ma H. 2013. Application of horseradish peroxidase modified nanostructured Au thin films for the amperometric detection of 4-chlorophenol. Colloids Surf B: Biointerfaces 103:129–135.

Ramnani P, Saucedo NM, Mulchandani A. 2016. Carbon nanomaterial-based electrochemical biosensors for label-free sensing of environmental pollutants. Chemosphere 143:85–98.

Rebollar-Pérez G, Campos-Terán J, Ornelas-Soto N, Méndez-Albores A, Torres E. 2015. Biosensors based on oxidative enzymes for detection of environmental pollutants. Biocatalysis 1.

Rodriguez-Mozaz S, de Alda MJL, Barceló D. 2006. Biosensors as useful tools for environmental analysis and monitoring. Anal Bioanal Chem 386(4):1025–1041.

Rodriguez-Mozaz S, De Alda ML, Barceló D. 2005. Analysis of bisphenol A in natural waters by means of an optical immunosensor. Water Res 39(20):5071–5079.

Ronkainen NJ, Halsall HB, Heineman WR. 2010. Electrochemical biosensors. Chem Soc Rev 39(5):1747–1763.

Saleem M. 2013. Biosensors a promising future in measurements. IOP conference series. Mater Sci Eng. IOP Publishing 51(2013):012012. https://doi.org/10.1088/1757-899X/51/1/012012

Sassolas A, Prieto-Simón B, Marty J-L. 2012. Biosensors for pesticide detection: New trends. Am J Analyt Chem 3(3):210.

Satoh I, Iijima Y. 1995. Multi-ion biosensor with use of a hybrid-enzyme membrane. Sens Actuators B Chem 24(1):103–106.

Shin HJ. 2010. Development of highly-sensitive microbial biosensors by mutation of the nahR regulatory gene. J Biotechnol 150(2):246–250.

Taylor CJ, Bain LA, Richardson DJ, Spiro S, Russell DA. 2004. Construction of a whole-cell gene reporter for the fluorescent bioassay of nitrate. Anal Biochem 328(1):60–66.

Turdean GL. 2011. Design and development of biosensors for the detection of heavy metal toxicity. Int J Electrochem. 2011:15. Article ID 343125. https://doi.org/10.4061/2011/343125

Verma N, Bhardwaj A. 2015. Biosensor technology for pesticides—a review. Appl Biochem Biotechnol 175(6):3093–3119.

Vigneshvar S, Sudhakumari C, Senthilkumaran B, Prakash H. 2016. Recent advances in biosensor technology for potential applications-An overview. Front Bioeng Biotechnol 4.

Vogrinc D, Vodovnik M, Marinsek-Logar R. 2015. Microbial biosensors for environmental monitoring. Acta agriculturae Slovenica 106(2):67–75.

Vopálenská I, Váchová L, Palková Z. 2015. New biosensor for detection of copper ions in water based on immobilized genetically modified yeast cells. Biosens Bioelectron 72:160–167.

Wang J-j, Liu W-h, Chen D, Xu Y, Zhang L-y. 2014. A micro-machined thin film electro-acoustic biosensor for detection of pesticide residuals. J Zhejiang Univ Sci C 15(5):383–389.

Wang J. 2006. Analytical electrochemistry. Third edition. Hoboken, NJ, USA: John Wiley & Sons. https://doi.org/10.1002/0471790303.ch1

Wang L, Sipe DM, Xu Y, Lin Q. 2008. A MEMS thermal biosensor for metabolic monitoring applications. J Microelectromech Syst 17(2): 318–327.

Ziegler C. 2000. Cell-based biosensors. Fresen J Anal Chem 366(6–7): 552–559.