Opportunities and challenges of biosensors for pollution detection and monitoring of the Bay of Bengal

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Abstract:

From the beginning of the first reordered human settlement in this Bengal province to the present, people living in this area have been mostly dependent on the Bay of Bengal and its various resources. Human beings have been collecting the raw material from the ocean to use in the different production processes. It is also a potential source of fossil fuel and the largest source of animal protein. Along with this, human kind use the sea for the transportation of goods and services. In addition, to keep our terrestrial environment worth living in, the marine environment plays an important role. However, overdoing such types of activities, mankind are systematically destroy this delta, the Bay of Bengal, and its ecosystem in various ways. Therefore, it is high time to prevent pollution and protect this reservoir resources, the Bay of Bengal. The sustainable way of doing this is to emphasize monitoring of pollution. Biosensors in the medical and industrial sectors are esstablished because of their biocompatibility, specificity, accuracy, and sensitivity. Some biosensors have already been developed for monitoring environmental pollution and their good performance have been well documented . But, the case of detecting ocean pollution is still under consideration. So, now designing a biosensor for pollution detection in the Bay of Bengal and protecting the reservoir of resources is necessary to achieve the sustainable development goal. Though the method has some limitations, it is nonetheless a new window to harvest the benefits.

Keywords: Biosensors, Pollution, Bay of Bengal, Maritime, Bangladesh.

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1. Introduction

A biosensor is an electrical analytical device that converts the bioreceptor signal into a measurable electrical signal proportional to the concentration and displayed accurate results for further analysis. A typical biosensor comprises three main elements, such as biological means, a transducer, and an electronic system (1). The working mechanism is a signal from a biological source further converted by the transducer to a detectable signal electrochemically, optically, acoustically, mechanically, calorimetrically, or electronically which then compare with the standard given concentration and produce a final result (2).

Based on transducer biosensors can be classified as Electrochemical biosensors, Electrical biosensors, Optical biosensors, Piezoelectric (mass-sensitive) biosensors, and Calorimetric (thermometric) biosensors (3). Based on biological recognition elements or bioreactors, biosensors can be further classified as Enzyme-based biosensors, Electrochemical immunosensors, Nucleic acid-based biosensors, Cell-based biosensors, and Biomimetic sensors (4).

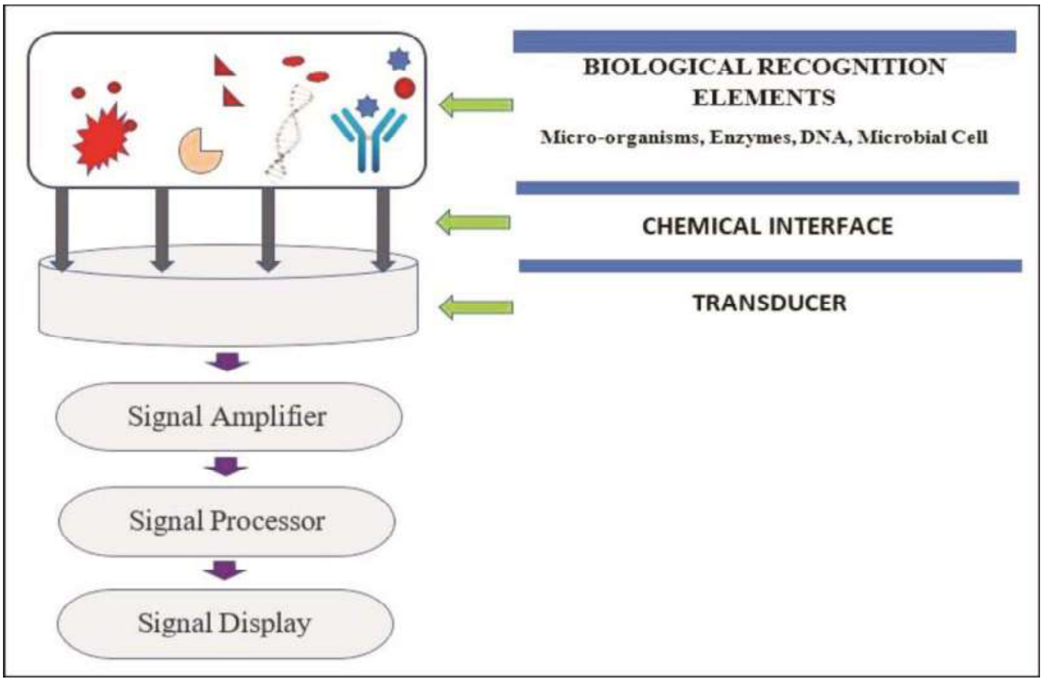

Figure 1: Schematic representation of a typical biosensor.

Around 100 papers have been published each year relating to biosensors and the description of the systems that could be of relevance to marine measurements. Previously some expert taxonomists have carried out identification using a microscope, but recently molecular biology methods enriched this field, and consequently, numerous biosensors have been developed. Monterey Bay Aquarium Research Institute developed automated RNA hybridization probes which can detect toxic algae and other microorganisms. In the future, using nucleic acid sensors, we can facilitate future ecosystem studies. For eutrophication assessments that help eliminate harmful algal toxins in the water column, recently launched a microbial biosensor. This biosensor is based on denitrifying bacteria, which can detect total oxidizable nitrogen, phosphate, and silicate. If we cannot measure seafood safety which is related to eutrophication leads to harmful diseases like diarrhoea, memory loss, or even paralysis and death. So, to protect consumer health from contaminated seafood algal toxins, antibody-based biosensors, depending on the mechanisms of action of the toxins, have been developed. From the above examples of some biosensors, we can conclude that some biosensors can provide information about interactions with biological materials. In contrast, others are advantageous over field applicability, automation, or cost (31). This review article describes the necessity of biosensors for pollution detection of the Bay of Bengal which is necessary for blue governance and sustainable economic growth in near future.

2. How marine pollution can effects on human and animals' health?

Releases of toxic metals to the marine environment directly or indirectly since the beginning of the Industrial Revolution have increased during the last two decades. Among the released toxic substances' mercury is one of the sources which have a negative physiological and psychological impact on a human being. Exposure to methylmercury, due to the consumption of mercury-contaminated fish from marine sources during pregnancy of a mother, to the new-born babies have an impact on the losses of cognitive function. Exposure to methylmercury, an adult can also have serious consequences, like mental retardation, lower IQ levels. Marine pollution due to plastic waste ranges in size from floating barrels to sub-microscopic particles and fibres have a deadly impact on marine populations and also on terrestrial people. Other than toxic methylmercury and plastics majority of manufacturing chemicals potentially damage ecosystems or harm human health. Some manufacturing chemicals which was released every day in the marine environment are responsible for a range of human diseases such as cardiovascular disease, developmental defects in new-born infants, development of neurotoxicity that leads to attention disorder. Other complications include problem in behaviour and execution of function, and social behaviour, damaging human and ecosystem health through disruption of endocrine function. Such pollution also increases the risk of diabetes and metabolic disorder that increase the risk of mortality from these chronic diseases. The name of such toxic compounds are Halogenated aromatic hydrocarbons (HAHs), Perfluoroalkyl substances (PFAS), Organophosphorus flame retardants (OPFRs), Polynuclear aromatic hydrocarbons (PAHs), Pesticides, Organometals, and so on (8).

3. Why is Bay of Bengal important for us?

It is the largest bay in the world. The Bay of Bengal plays an important role in our daily life as we get 70 percent oxygen from it, which is necessary for our breathing. Along with this, it controls our terrestrial environment by absorbing carbon dioxide and temperature. The Bay of Bengal is the source of around 16 percent of the animal protein we consume every day. It is also essential for the trophic chain of the ecosystems, the place for a good vacation, sources of income for thousands of people, and source of bioactive compounds for designing drugs that can save us from sufferings (7).

4. How do we pollute Bay of Bengal?

We are Human beings who pollute marine life and their environment every day, called nonpoint source pollution, which occurs as a result of runoff. Nonpoint source of pollution includes septic tanks, cars, trucks, and boats, plus larger sources, such as farms, ranches, and forest areas. Millions of motor vehicle engines drop small amounts of oil onto roads and parking lots each day, which ultimately makes its way to the sea. Besides, toxic chemicals from industries include oil, mercury, lead, pesticides, and other heavy metals, also contaminated the ocean environment. This pollution results in damage to the environment and the health of all organisms, and also the economic structures worldwide (5,6).

5. Sources of pollutions

There are several sources, activities due to amenities or sources of rivers run off, which is responsible for our ocean became polluted day by day. What our activities on land, in the rivers and in the air also are ultimately ended up in the ocean. Some of the reasons are mentioned below,

5.1 Ship breaking and Shipbuilding industries

Globally Bangladesh is leading in Shipbuilding and shipbreaking industry. In the coastal area, there are about forty ship breaking and recycling industries operated in Bangladesh. These industries contributed an annual average of 1–1.25 million tons of scrap steel for re-rolling industries (35). In the shipbuilding and shipbreaking area, the environment, including soil, water, and gaseous, is polluted due to the heavy metal. These heavy metals have a direct and indirect effect on our health and can destroy the ocean's primary productivity, phytoplankton, zooplankton, benthos, and fish species diversity. The actual concentration of the Ni, Cu, Cd, Fe, Mn, and Pb in the nearshore of the Bay of Bengal is 0.0055–0.1091 mg/L, 0.119–0.192 mg/L, 0.0017–0.098 mg/L, 0.1561–60.454 mg/L, 0.52–1.80 mg/L, and 0.0964–0.694 mg/L respectively. This range is around ten times higher than the recommended by WHO/FEPA for drinking even after if we can remove salt from water (36).

5.2 Oil spillage

Oil pollution from ships may be due to the intentional release of waste oil from vessels or due to unavoidable circumstances. Unavoidable circumstances include people making mistakes or being stupidly breaking down equipment, natural disasters such as hurricanes, terrorist acts, countries at war, vandals, or illegal dumpers. Due to increased demand, shipping activities in the port area are getting higher day by day. Lacking effective legislation and monitoring cell and lack of treatment facilities, foreign and domestic ships, and trawlers may discharge their oily waste in the sea area of Bangladesh. On the other hand, sometimes unintentional spillage occurs during the loading and unloading of oil at the port (37). Along with river runoff mixed with releasing oil, oily water and sludge ultimately come into contact with the ocean water. This oil pollution destroys agriculture and fisheries, and when it is mixed with the ocean, it eliminates the ocean's ecosystem.

5.3 Hazardous chemical from rivers

In to the edge of globalization, people are moving from their traditional approach to industry because industry gives them more feedback than the agricultural sector. In Bangladesh, industrial sectors are mainly manufacturing and construction, including textile, leather, food products, tobacco products, pharmaceuticals, medicinal chemicals, machinery and equipment, paper & newsprints, cement, Sugar, etc. (38, 39). Besides, the farmers are trying to increase their production by using fertilizers and pesticides to meet the increasing demand. Toxic chemicals used in the industries are intentionally or unintentionally discharged into rivers. Dirty water used to cool down machines is put back into the rivers. Dumping waste products are the sources of several tonnes of waste products that go into the rivers. All these mentioned sources of water with chemical hazards fall into the rivers and ultimately ended up in the ocean.

5.4 Microplastics

All over the world's including Bay of Bengal are polluted by two types of plastics such as large plastics waste and microplastics. According to the recent study it was estimated that every year around 10 million metric tons plastic waste entered in to the ocean environment worldwide (40). Large plastic waste is visible on the naked eye and have financial drawbacks in the tourist areas and maritime industries as well as it also brings sufferings for the wildlife living beings (41, 42). On the other hand, plastic particles below 5 mm in size and are not visible on the naked eye can accumulate into the food chain. This microplastics are now being major concern for the researchers as it is becoming toxic for the human and other wildlife living beings. Microplastics are present in the natural environment in the two forms, primary microplastics and secondary microplastics. The former one is produced directly by the abrasion of large plastics during manufacturing and through other process but the later one produced by the degradation of large plastics sources (43). From the Bangladesh perspective it was said that in the Bay of Bengal every day the amount entered is up to 3 billion microplastic particles (44). As these microplastics can get accumulated in to the food chain and can cause oxidative stress through, translocation, inflammatory lesions, etc. In human it creates neurotoxicity, metabolic disturbances and also can increase the risk of cancers (45).

5.5 Ballast water

According to the Ballast water convention, Ballast water is “The Water with its suspended matter taken on board a ship to control trim, list, draught, stability or stresses of the ship”. Ballast water is necessary to manage the ship’s stability. Earlier ships were used rocks and sand as a solid ballast. In the ship ballast is equipped as 25-30% of a ship’s dead weight tonnage, this size can be varied according to the ship’s design. After the invention of pumping system water is pumped in to the ballast tank and again discharged when ballast water no longer needed, actually when ship’s need to be lightened. These ballast water brings major concern to the researcher as it possesses major threatened for the public health, marine environment and the economy as well. As ballast water pumped in from one place and discharged another place so these water also a source of invasive species, which is alarming for the ecosystem. Sometimes these ballast water became the vector of some deadly diseases which may bring public health issues (46). So, this is now becoming the growing concern for the researchers, ecologists and public health experts to manage ballast water.

6. Opportunities of biosensors for the detection of Pollution of Bay of Bengal

For the detection of marine contamination, the number of biosensors designed is still relatively small and for the detection of Bay of Bengal pollution it is tends to zero. Many of the systems described below for the detection of pollution of other water bodies are may potentially applicable for our Bay of Bengal pollution measurements.

6.1 Role of biosensors for the detection of Bay of Bengal pollution

For the detection of Bay of Bengal pollution generally, be based on collecting samples and laboratory-based instrumental analysis. In this way, sampling time and sampling point may not sometimes provide practical information to get the original scenario. In this context, biosensors are designed to provide us information regarding pollutants in a specific area continuously. It is helpful because of its biocompatibility, specificity, accuracy, sensitivity. At the same time, biosensors offer meaningful determination of specific chemicals and their biological effects, such as toxicity, cytotoxicity, and genotoxicity (9). According to IUPAC, a biosensor is a self-contained integrated device using biological recognition element, can provide quantitative or semi-quantitative analytical information. A well-designated biosensor does not need additional processing steps, such as reagent addition; instead, it is not disposable after one measurement, and also it is rapid and reproducible (10). With the advent of high methodologists, a biosensor can monitor the increasing number of analytes of environmental pollution quickly and cheaply. In the practical aspect, the use of biosensors for the detection of marine pollutions is still under consideration. Still, in the medical and pharmaceuticals sector, it is already enriched by the use of biosensors. Due to pollution, some of the essential physical, chemical, and biological variables changed. To measure the changed concentration of the variables, we can use electrochemical biosensors (11) as a consequence of the pollution. The characteristics qualities that should be included in our Bay of Bengal area are portability, deploy ability, and fabricability. (12, 13).

6.2 Detections of hazardous pollutants

As per our early discussion, pollutants can reach the marine environment through Shipbuilding industries, oil spillage, industrial chemical hazards from river runoff; agricultural used chemical runoff, microplastics, ballast water, domestic wastewater from sewage treatment works, and so on. Along with releases from ships by leaching anti-biofouling agents or accidental events following accidents involving oil tankers or cargo ships carrying hazardous chemicals, all mentioned sources contribute to marine pollution. (14).

The principle of acetyl-choline esterase inhibition and some antibodies are being used in the biosensors to detect pesticides by creating immunosensors (15). Some developed immunosensors are Irgarol (16), Paraquat (17), and Isoproturon (18) for the detection of estuarine water samples at levels down 0.1 g/l. One notable example of immunosensor can retain recognition properties at mixed aqueous/organic solvent soil extracts (19) for the herbicide 2,4-dichlorophenoxyacteic acid 2,4-D.

For the detection of chlorophenols, pesticides, and surfactants from the seawater a whole-cell sensor system that has been applied. In this biosensor marine algae Spirulina subsalsa coupled to a Clark-type oxygen electrode was used (20). Similarly, a whole cell sensor based on C. vulgaris and fibre optic signal for the detection of atrazine, simazine, iso-proturon and diuron, which is photosystem II inhibitors (21). The advantages of the whole cell system over the enzymatic or affinity sensors are that it can measure bioavailability and potentially physiological responses. The other side of the coin to the whole cell sensors is signals are generally less specific.

Genetic engineered bacteria coupled with a suitable transducer can recently respond to particular stresses or toxicity, which can have acute or chronic toxic effects. (22; 23; 24; 25). For the construction of optical sensors use of the lux operon or green fluorescent protein is widespread. For example, to detect phenanthrene toxicity from soil samples, some scientists already constructed a system (26) and mentioned a range of related systems. A review was also summarised for environmental monitoring (27).

Another most alarming widespread toxic substance is tributyltin (TBT), an antifouling organotin compound, which was previously banned by the International Maritime Organisation (IMO) is still prevalent in many sediments (28). The harmful effects that can observed by the scientists which was documented on biota are direct toxicity, shell thickening in oysters, a decline in recruitment of their juvenile stages, and endocrine disruption (imposex). A bioluminescence-based bioassay for the detection of organotin compounds was used (29). The detection limit of the organotin presented at the Eighth World Congress on Biosensors, a sensor based on bacteria immobilization matrix and the mentioned luminescent detection limit, is 1 nM TBT (325 ng/l) (30).

6.3 Sensors for observing ecosystem status

Many different methodologies exist to specify sensors for ecosystem status. The things we should look at for measurement inform us about biogeochemical cycles and primary productivity to overall marine productivity. Following primary producers next look into secondary production and how energy transfers from one trophic level to the next trophic level, which is not so easy to quantify with a sensor. Biogeochemical cycles are directly related to ecosystem status, so we should focus on oceanic carbon measurements and observation of ocean nutrients environments. These elements are essential to control water quality and critical criteria under many EU directions, OSPAR comprehensive procedure assessments (32). When we look into biogeochemical cycles, the essential elements are oxygen, carbon dioxide, pH, and functional groups of micro-organisms. Oxygen is vital in the marine ecosystem both in the case of primary production and also detection of low oxygen events. Oxygen concentration in sediments and water column on carbon fate and cycling in terms of benthic and pelagic coupling rates. Latest biosensors named, seabird oxygen sensor is based on Clark polarographic membrane and optodes (33). For marine acidification carbon dioxide and pH concentration also bring much concentration along with the functional groups of micro-organisms (34). So, to measure ecosystem status all the mentioned parameters should be monitored carefully using a single biosensor. For measurements from Smart-Buoys and other automated platforms have been produced extremely useful data series.

7. Challenges of biosensors for the detection pollution of Bay of Bengal

It is reported that the development of commercially available biosensors is due to the blessing of science and technology. The biosensors are reliable because of their specificity, sensitivity, and reproducibility, and also reliability. In the medical sector, the diagnosis number of diseases using biosensors already became familiar, but it still lacks the point-of-care (POC) applications. The POC includes portability, cost-effectiveness, responsiveness, and disposability. Applications of biosensors in medical sectors still have challenges that need to address for large-scale production (47). Following medical sectors, applications of biosensors on monitoring some concerning areas like marine environment, agriculture, and marine food industry are underway. The challenges related to the development and construction of biosensors that can monitor Bay of Bengal pollutions are the detection of small molecules, reusability, and satisfactory stability (48, 49).

The sensitivity of this surface depends on the sensing layer thickness (50-54). If the surface layer is beyond the range of 30 to 150 μm, it may not work. In another way, if the surface layer is too thin, the electrode surface will be exposed, and if it is too thick, the sensitivity will be decreased (50). The antibody-based biosensors will create the problem due to the strength and irreversibility of antibody-antigen binding. In this case, without damaging the antibody layer regeneration and reusability is not possible (55). In addition, antibody-based Si electrodes are not compatible with the extreme pH values. So, biosensors reusability, in those environments, can be problematic (56). Moreover, challenges also may arise to detect heavy metals and molecules that come from agricultural runoff because the electrode surface may face the problem with the charge-transfer resistance through the polymer-protein layer (57,58).

8. Conclusions

In a word, a biosensor is a lab-in-a-chip that was designed to convert biological signals to measurable electric signals. It is reliable because of its sensitivity, specificity, portability, ease of disposal, and cost-effectiveness. For achieving sustainable development goal 13, our strategy should be to ensure the health of the Bay of Bengal, the reservoir of resources. Hazardous pollutions come from different sources that are harmful not only for the Bay of Bengal's ecosystems but also for living on the land. To meet our daily amenities, intentionally and unintentionally, we are destroying our oasis of Bangladesh, the Bay of Bengal. Effective monitoring is mandatory to tug the pollutions of the Bay of Bengal. To ensure proper monitoring, we can emphasize designing and manufacturing an effective biosensor to eliminate this pollution-like vicious cycle. However, we may have to face some challenges in developing an effective biosensor as it is difficult to select suitable bioreceptors for its harsh diversified environment. Nonetheless, to mitigate the pollutions problem of the Bay of

Bengal, it is high time to bridging the gap between theoretical aspects and design an effective Biosensor, to face future challenges.

Table 1: Common Biosensors used for Pollution Detection in the Environment

Contaminant Detected	Sensing Material	Biological Recognition Element/s	Category of Biosensor	Response Range	Parameter of Detection
Pesticides					
Paraoxon (59-62)	Gold SPE[2] and cysteamine SAM[3]	Enzyme (AChE[1])	Electrochemical (amperometric)	Up to 40 ppb	2 ppb (*1)
	SPE[2]with carbon black nanoparticles	Enzyme (butyrylcholinesterase)	Electrochemical (voltammetric)	Up to 30 $\mu g\ L^{-1}$	5 $\mu g\ L^{-1}$ (*1)
	Iodine-starch	Enzyme (AChE[1] and ChO[4])	Optical (colorimetric)	10–400 ppb	4.7 ppb (*2)
	GCE[5] and gold nanorods	Enzyme (AChE[1])	Electrochemical (amperometric)	1 nM^{-5} µM	0.7 nM (*1)
Methyl parathion (63-67)	SPE[2] with Fe_3O_4 and Gold nanoparticles	Enzyme (hydrolase)	Electrochemical (impedimetric)	0.5–1000 ng $m\ L^{-1}$	0.1 ng $m\ L^{-1}$
	Graphite and macroalgae	Enzyme (AChE[1])	Electrochemical (amperometric)	0–1500 ng $m\ L^{-1}$	1.5–1.8 ng $m\ L^{-1}$ (*1)
	Carbon paste electrode and reticulated spheres structures of $NiCo_2S_4$	Enzyme (AChE[1])	Electrochemical (impedimetric)	1.0 pg $m\ L^{-1}$ –10 ng $m\ L^{-1}$	0.42 pg $m\ L^{-1}$ (*3)
	Carbon paste electrode with chitosan, gold nanoparticles, and Nafion	Enzyme (AChE[1])	Electrochemical	0.01 pg mL−1–10 ng $m\ L^{-1}$	5 fg $m\ L^{-1}$
	Microplate with silica nanoparticles and Pei[6] hybrid	*Sphingomonas sp.* cells	Optical	0.1–1 ppm	0.01 ppm
Chlorpyrifos (68-71)	SPCE[7] and IrO_x nanoparticles	Enzyme (tyrosinase)	Electrochemical (impedimetric)	0.01–0.1 µM	3 nM
	Boron-doped diamond electrode with gold nanoparticles and carbon spheres	Enzyme (AChE[1])	Electrochemical (voltammetric)	0.01 nM–0.1 µM	0.13 pM (*4)
	Carbon black and GO[8]/ Fe_3O_4	Aptamers (#1)	Electrochemical (voltammetric)	0.29 nM–0.29 mM	94 pM (*3)

	GCE[5] with NiO nanoparticles-carboxylic graphene-Nafion	Enzyme (AChE[1])	Electrochemical (amperometric)	0.1–10 nM	0.05 pM ([*2])
Dichlorvos (72-74)	QD[9] and acetylcholine	Enzyme (AChE[1] and ChO[4])	Optical (fluorescence)	4.49–6780 nM	4.49 nM ([*1])
	Platinum electrode with ZnO	Enzyme (AChE[1])	Electrochemical (voltammetric)		12 pM ([*1])
	Ionic liquids-gold nanoparticles porous carbon composite	Enzyme (AChE[1])	Electrochemical (impedimetric)	0.45 pM–4.5 nM	0.3 pM ([*1])
Acetamiprid (75-78)	Gold nanoparticles	Aptamers ([#2])	Optical (colorimetric)	75 nM–7.5 µM	5 nM ([*3])
	Silver nanoparticles and nitrogen-doped GO[8]	Aptamers ([#3])	Electrochemical (impedimetric)	0.1 pM–5 nM	33 fM ([*3])
	Platinum nanoparticles	Aptamers ([#3])	Electrochemical (impedimetric)	10 pM–100 nM	1 pM
Atrazine (78-81)	Gold nanoparticles	Antibodies (monoclonal)	Electrochemical (voltammetric)	0.05–0.5 ng m mL^{-1}	0.016 ng mL^{-1} ([*3])
	SWCNT	Antibodies (monoclonal)	Electrochemical (FET[17])	0.001–10 ng mL^{-1}	0.01 ng m mL^{-1}
	Platinum nanoparticles	Aptamers ([#4])	Electrochemical (impedimetric)	22 pg m L^{-1}–0.22 µg m L^{-1}	2.2 pg mL^{-1}
	Magnetic beads functionalized with protein G	Phage/antibody (monoclonal complex)	Electrochemical (amperometric)	0.0001–0.001 pg m L^{-1}	0.2 pg m L^{-1}
Pirimicarb (82,83)	Carbon paste electrode with MWCNT[10]	Enzyme (laccase)	Electrochemical (voltammetric)	0.24–2.7 mg L^{-1}	43 µg L^{-1}
	Prussian blue-MWCNT[10] SPE[2]	Enzyme (AChE[1])	Electrochemical (amperometric)	1 µg L^{-1}–1 g L^{-1}	53.2 ng L^{-1} ([*5])
Carbofuran (71, 84, 85)	IrO_x-chitosan nanocomposite	Enzyme (AChE[1])	Electrochemical (voltammetric)	5–90 nM	3.6 nM ([*2])
	GCE[5] with GO[8] and MWCNT[10]	Enzyme (AChE[1])	Electrochemical (amperometric)	68–3672 pM	136 pM
	GCE[5] with NiO nanoparticles-carboxylic graphene-Nafion composite	Enzyme (AChE[1])	Electrochemical (amperometric)	1 pM–0.1 nM	0.5 pM ([*2])
Carbaryl (86-89)	Gold electrode with cysteamine SAM[3]	Enzyme (AChE[1])	Electrochemical (impedimetric)	1–9 µM	32 nM

	Interdigitated array microelectrodes with chitosan	Enzyme (AChE[1])	Electrochemical (impedimetric)	4.96–496 nM	3.87 nM
	MWCNT[10] and GO[8] nanoribbons structure	Enzyme (AChE[1])	Electrochemical (amperometric)	5–5000 nM	1.7 nM (*3)
	Porous GCE[5] with GO[8] network	Enzyme (AChE[1])	Electrochemical (amperometric)	1.49–30.3 nM	0.74 nM (*3)
Pathogens					
Legionella Pneumophila (90-93)	Gold substrate with streptavidin-conjugated QD[9]	Nucleic acids (#5)	Optical (SPR[12])	104–108 CFU mL^{-1}	104 CFU mL^{-1}
	Gold substrate with protein A SAM[3]	Antibody (polyclonal)	Optical (SPR[12])	103–106 CFU mL^{-1}	103 CFU mL^{-1}
	SPCE[7] with Fe_3O_4@polydopamine complex	Antibody (polyclonal)	Electrochemical (amperometric)	104–108 CFU mL^{-1}	104 CFU mL^{-1}
	Gold gratings substrate	Antibody (polyclonal)	Optical (SPR[12])		10 CFU mL^{-1}
Escherichia coli (94-96)	Gold substrate	Polymerizable form of histidine	Optical (SPR[12])		3.72 × 105 CFU mL^{-1}
			Piezoelectric (QCM[13])		1.54 × 106 CFU mL^{-1}
	Gold electrode	Polymerizable form of histidine	Electrochemical (capacitive)	102–107 CFU mL^{-1}	70 CFU mL^{-1}
	GCE[5] with polydopamine imprinted polymer and nitrogen-doped QD[9]	Antibody (polyclonal)	Optical (electrochemiluminescence)	10–107 CFU mL^{-1}	8 CFU mL^{-1}
Bacillus subtilis (97)	Gold electrode with SWCNT[14]	Antibody (polyclonal)	Electrochemical (amperometric)	102–1010 CFU mL^{-1}	102 CFU mL^{-1}
Potentially Toxic Elements					
Hg^{2+} (98-101)	Optical fibre platform	Nucleic acids (#6)	Optical (evanescent-wave optical fibre)	0–1000 nM	1.2 nM (*2)
	MOF[15] (UiO-66-NH_2)	DNA	Optical (fluorescence)	0.14 µM	17.6 nM
	Gold substrate with vertically aligned SWCNT	Nucleic acids (#7)	Electrochemical (voltammetric)	10 fM–1 µM	3 fM (*3)
	SWCNT[11] and Co Fe_3O_4@Ag substrate	Nucleic acids (#8)	Optical (SERS[16])	1 pM–100 nM	0.84 pM (*3)
Pb^{2+}(102-104)	Carboxylated magnetic beads	DNAzymes (#9)	Optical (fluorescence)	0–50 nM	5 nM (*3)

	Graphene QD[9] and gold nanoparticles	DNAzyme (#10)	Optical (fluorescence)	50 nM–4 µM	16.7 nM
	Micro-spin column	Aptamers (#11)	Optical (fluorescence)	100–1000 nM	61 nM (*3)
Toxins					
Microcystin (108-110)	Graphene	Antibodies (monoclonal)	Electrochemical (impedimetric)	0.05–20 ng mL^{-1}	50 pg mL^{-1}
	Gold electrodes with MoS_2 and gold nanorods	Antibodies (monoclonal)	Electrochemical (voltammetric)	0.01–20 ng mL^{-1}	5 pg mL^{-1} (*3)
	SPE[2]	Enzyme (protein phosphate 1)	Electrochemical (voltammetric)	0.93–40.32 mL^{-1}	0.93 ng mL^{-1} (*1)
Endocrine Disrupting Chemicals					
Bisphenol A (116-118)	Gold nanoparticles	Aptamers	Optical (fluorescence)	1–10000 ng mL^{-1}	0.1 ng mL^{-1}
	Optical fibre surface	Aptamers (#13)	Optical (evanescent-wave optical fibre)	460 pg mL^{-1}–22.8 ng mL^{-1}	0.45 ng mL^{-1} (*2)
	Molybdenum carbide nanotubes	Aptamers (#14)	Optical (fluorescence)	0–91.3 ng mL^{-1}	0.23 ng mL^{-1}
Nonylphenol (119)	SWCNT[14]	Antibodies (monoclonal)	Electrochemical (FET[17])	5–500 ng mL^{-1}	5 ng mL^{-1}
17β-estradiol (120-122)	CdSe nanoparticles and TiO_2 nanotubes	Aptamers (#15)	Photo-electrochemical	0–80 pM	33 fM
	Gold electrode with MPA[18] SAM[3]	Antibodies	Electrochemical (voltammetric)	2.25–2250 pg mL^{-1}	2.25 pg mL^{-1}
	Gold electrode with MUA[19] SAM[3]	Antibodies	Electrochemical (capacitive)	1–200 pg mL^{-1}	1 pg mL^{-1} (*3)

Table 2: List of Marine Biosensors Used to Detect Pollution in the Ocean

Contaminant Detected	Sensing Material	Biological Recognition Element/s	Category of Biosensor	Response Range	Parameter of Detection
Pesticides					
Acetamiprid (76)	Gold nanoparticles, MWCNT[10], and rGO[11] nanoribbons	Aptamers (#3)	Electrochemical (impedimetric)	50 fM–10 µM	17 fM (*3)

Toxins					
Brevetoxin-2 (105,106)	Gold electrodes with cysteamine SAM[3]	Aptamers (#12)	Electrochemical (impedimetric)	0.01–2000 ng mL^{-1}	106 pg mL^{-1}
	Microelectrode array with platinum nanoparticles	Cardiomyocyte Cells	Electrochemical (voltammetric)	5.6 ng mL^{-1}–1.4 µg mL^{-1}	1.55 ng mL^{-1}
Saxitoxin (106,107)	Microelectrode array with platinum nanoparticles	Cardiomyocyte Cells	Electrochemical (voltammetric)	5.6 ng mL^{-1}–1.4 µg mL^{-1}	0.35 ng mL^{-1}
		Aptamers	Optical (interferometry)	10–2000 ng mL^{-1}	0.5 ng mL^{-1}
Okadaic acid (110-112)	Gold electrode with carboxymethylated surface	Antibodies	Optical (SPR[12])		0.36 ng mL^{-1}
	Graphene	Antibodies (monoclonal)	Electrochemical (FET[17])	0.05–300 ng mL^{-1}	0.05 ng mL^{-1}
	Carboxylic acid modified magnetic beads and CdTe QD[9]	Antibodies (monoclonal)	Optical (fluorescence)	0.2–20 ng mL^{-1}	0.05 ng mL^{-1}
Domoic acid (113-115)	Gold electrode with carboxymethylated surface	Antibodies	Optical (SPR[12])		1.66 ng mL^{-1}
	SWCNT[14]	Antibodies (monoclonal)	Electrochemical (FET[17])	10–500 ng mL^{-1}	10 ng mL^{-1}
	Glass side chip with gold surface	Optical (SPR[12])	Antibodies	0.1–2 ng mL^{-1}	0.1 ng mL^{-1}

Notes:

1. AChE: acetylcholinesterase, 2. SPE: screen printed electrode, 3. SAM: self-assembled monolayer, 4. ChO: choline oxidase, 5. GCE: glassy carbon electrode, 6. PEi: polyethyleneimine, 7. SPCE: screen printed carbon electrode, 8. GO: graphene oxide, 9. QD: quantum dots, 10. MWCNT: multi-walled carbon nanotubes, 11. rGO: reduced graphene oxide, 12. SPR: surface plasmon resonance, 13. QCM: quartz crystal microbalance, 14. SWCNT: single-walled carbon nanotubes, 15. MOF: metal organic framework, 16. SERS: surface enhancement Raman spectrum, 17. FET: field effect transistor, 18. MPA: 3-mercaptopropionic acid, 19. MUA: 11-mercaptoundecanoic acid;

Acknowledgment

The authors would like to thank BSMRMU authority for providing lab and library facilities to write the article.

Conflict of interest

We don’t have any conflict of interest with anyone.

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