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Research on High-Performance Biosensors for Effective Marine Pollution Monitoring

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Abstract: This article expounds that human activities have caused severe marine pollution, and biosensors have become key tools for marine pollution monitoring. It elaborates on their composition, classification, and working principles. It focuses on introducing various sensors and their detection effects in different aspects of marine pollution detection, such as organic pollutants (hydrocarbons, organophosphorus, organic nitrogen compounds), heavy metal ions, microorganisms, and biological toxicity assessment. It also looks forward to the future development of multi-characteristic sensing platforms that can be integrated into various marine platforms to form coastal sensor networks. At the same time, it is necessary to address challenges such as the variability of the marine environment, conduct multi-disciplinary verification, and optimize the quality and performance of sensors. This review found that biosensors are important tools for detecting various marine pollutants, providing effective solutions for marine environmental monitoring and protection. Future advances in sensor technology, multi-characteristic platforms, and artificial intelligence integration will improve their performance and scalability, supporting sustainable marine resource management. However, this study relied on secondary data, which highlights the need for more empirical studies and field tests in different marine habitats to evaluate the actual performance of marine biosensors.

Keywords: Marine Pollution, Biosensors, Environmental Monitoring, Sensor Technology

1. Introduction

Over the past few decades, human activities have introduced a large number of pollutants into the ocean. The sources of marine pollutants are extensive, including heavy metals, organic pollutants, excessive nutrients, microplastics, etc. Generally, these pollutants enter the ocean through industrial and urban activities and rivers. The extraction of oil and gas and shipping activities directly discharge chemical pollutants into the marine environment. Common pollutants in seawater include stable trace elements (such as cadmium, lead, mercury, and tin), organic compounds (such as microplastics, pesticides, veterinary drugs, and pharmaceuticals), hydrocarbons (such as fuel and petroleum), and radionuclides [1].

Traditional marine pollution monitoring methods face many limitations, such as low sensitivity, long monitoring cycles, and lack of real-time data feedback, which make rapid detection and emergency response to pollutants difficult. There are many different kinds of contaminants in the marine environment, and their quantities fluctuate quickly. Relying on conventional monitoring

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technology frequently makes it difficult to accomplish fast and accurate monitoring and assessment. In order to overcome the difficulties associated with monitoring maritime pollution, it is imperative that more effective, sensitive, and flexible technologies be developed.

High-performance biosensors have gradually become an important tool in marine pollution research and monitoring due to their significant advantages in detection accuracy, real-time monitoring and environmental adaptability [1]. These sensors offer great support for the tracking, assessment, and control of pollution sources because they can detect pollutants in complicated maritime settings quickly and accurately. They can also provide real-time input on pollution situations. With an eye towards future technological development trends, this review will examine the most recent advancements in biosensor research for marine pollution monitoring, including their principles of operation, applications, and present technical obstacles and difficulties. Through the use of case analysis and literature review techniques, this article seeks to advance the use of related technologies in real-world environmental monitoring, offer fresh concepts and technical avenues for the prevention and control of marine pollution, and strengthen the capacity to safeguard human health and marine ecology.

2. The Overview of Biosensors

2.1. The Composition and working process of a biosensor

A biosensor is a device or probe that combines biological elements (such as enzymes or antibodies) with electronic components to generate measurable signals, and the electronic components detect, record, and transmit information about physiological changes or the presence of various chemical or biological substances in the environment [1]. Biosensors come in various sizes and shapes and can detect and measure low concentrations of specific pathogens or toxic chemicals and pH values. A typical biosensor consists of the following parts (see Figure 1): (a) analyte, (b) bioreceptor, (c) transducer, (d) electronics, and (e) display [2].

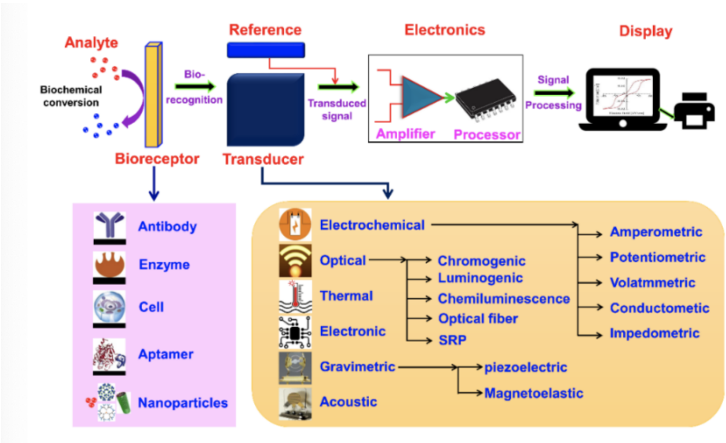

Figure 1: Biosensor Structure Schematic: Biosensor, Transducer, Electronics, and Display[2]

The working process of a biosensor is shown in Figure 1. It includes a biological receptor, the biomolecule, or biological tissue in a biosensor used to recognize the analyte. The signal generated during the interaction between the biological receptor and the analyte (appearing in the form of light, heat, pH, charge or mass change, plant or animal tissue, and microbial products) is called biological recognition. Signals then go through a transducer, a device that converts one form of energy into another. The transducer is a key component of a biosensor, converting the biological recognition event into a measurable electrical signal (related to the quantity or presence of the analyte or

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biological target) and connecting it to the quantity or presence. This energy conversion process is called signalization. The transducer generates optical or electrical signals proportional to the quantity of the analyte-biological receptor interaction. According to the working principle, transducers can be classified as electrochemical, optical, thermal, electronic, and gravitational transducers. Processing and preparing the transmitted signal. The electrical signal obtained from the transducer is amplified and converted into digital form. The processed signal is quantified by the display unit. The display unit consists of a user interpretation system, such as a computer or printer, used to generate output so that the user can read and understand the corresponding response. According to the end-user's prerequisites, the output can appear in the form of numerical, graphical, or tabular values or the form of a chart [2].

2.2. The Classification of Biosensors

There are various ways to classify biosensors, usually based on the detection principle (as shown in Figure 1), but they can also be classified by the biological recognition element [3], transducer type, application field, detection mode, etc. Most of the new sensors and biosensors developed in recent years are based on electrochemical or optical principles[1]. The classification boundaries of sensors are not clear. For example, Marzani et al. reported a wearable screen-printed biosensor that can be used to monitor pollutants on neoprene wetsuits [4]. The sensor works by measuring current, voltage, and potential changes to detect trace heavy metal pollutants, nitroaromatic explosives, and phenolic pollutants in seawater.

In marine pollution detection, it is more practical to classify sensors based on target analytes. Marine pollutants are of various types, with different chemical or biological properties, which determine the best detection method. By designing sensors for specific pollutants (such as heavy metals, organic pollutants, microplastics, etc.), the sensitivity, selectivity and accuracy of detection can be significantly improved. This classification method can effectively reduce interference and errors and improve monitoring efficiency and reliability. Therefore, this paper classifies biosensors for marine pollution detection according to the target analytes of the sensors, aiming to provide technical support for the efficient monitoring of different pollutants and promote the research and application of marine environmental protection.

3. Application of High-Performance Biosensors in Marine Pollution Detection

3.1. Detection of Organic Pollutants

Organic pollutants in the ocean mainly come from oil spills, agricultural runoff, industrial wastewater, and plastic degradation products. These pollutants include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), organic pesticides (such as DDT), and petroleum hydrocarbon compounds, which are persistent, toxic, and bioaccumulative, posing a serious threat to marine life and human health. Therefore, highly sensitive and rapid response detection methods are crucial in marine environmental monitoring.

3.1.1. Hydrocarbon Substances

Cennamo et al. developed an optical fiber biosensor for detecting naphthalene in seawater. The sensor combines an antibody layer with a plasmonic platform and consists of a functionalized (antibody) thin gold film (sputtered on the surface of a plastic optical fiber) [5]. The analytical signal is generated by the increase in the refractive index of the dielectric layer caused by the capture of the analyte by the biological receptor. The detection limit of this sensor is 0.76 ng/mL. Additionally, this sensor has remote detection capabilities. Shahar et al. developed an enzyme reflectometric biosensor for

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detecting halogenated organic pollutants in environmental water [6]. The target analytes are halogenated organic compounds, and the working principle of the sensor is based on the dehalogenation reaction catalyzed by haloalkane dehalogenase, which releases protons in the process. The dehalogenase immobilized on acrylic microspheres serves as a bioreceptor, and the chromogenic ion fluorescent dye serves as an optical proton probe. The release of protons causes the color of the fluorescent dye to change, thereby generating a measurable optical signal. The sensor exhibited a dynamic linear response range of 1-30 mg L-1 1,2-dichloroethane (DCA) (R2=0.9762) with a detection limit of 0.3 mg L-1. Application scenarios include environmental monitoring of water pollution. The advantages are high sensitivity and real-time monitoring capabilities. The disadvantages may be interference with other components in complex water bodies, affecting detection accuracy.

Biofuel cells are energy conversion devices based on electrochemical reactions, mainly used to convert the chemical energy of biomass into electrical energy. Nandimandalam et al. studied an electrochemical biosensor based on a two-chamber microbial fuel cell (Biofuel Cell, BFC) for the detection of chemical pollutants represented by hydrocarbons. The sensor used two microbial biofilms composed of mixed cultures of bacteria and microalgae as biocatalysts and sensing organisms on the cathode and anode of the bioelectrochemical cell, respectively. Microorganisms in the cathode generate potential through the metabolism of organic carbon, promoting electron flow, while microalgae on the anode act as an on-site oxygen supply source and electron acceptor. This continuous electron movement can be measured as an analytical signal, and the signal weakens when the surrounding medium is chemically contaminated. The results showed a good linear response to different concentrations of gasoline (in volume fraction 0-0.1%).

3.1.2. Organophosphorus Compounds

The extensive use of pesticides in agriculture is the reason for the large presence of organophosphorus compounds in the environment. Bao et al. [8] applied TiO2 nanofibers to an electrochemical sensor using amperometry for the detection of organophosphorus pesticides in seawater. The sensor was based on a functional nanocomplex composed of elastin-like polypeptide-organophosphorus esterase (ELP-OPH), bovine serum albumin (BSA), titanium dioxide nanofibers (TiO2NFs), and carboxyl-functionalized multi-walled carbon nanotubes (c-MWCNTs). Under optimized operating conditions, it showed a wide linear range, rapid response (less than 5 seconds), and detection limits as low as 12 nanomoles (for methyl parathion) and 10 nanomoles (for parathion) (signal-to-noise ratio of 3).

Malathion is a common organophosphorus (OP) insecticide widely used in agriculture [10]. Although there are currently many efficient and reliable methods for detecting and monitoring this pesticide, these methods have some limitations. Therefore, many studies have focused on developing electrochemical biosensors based on acetylcholinesterase (AChE) for the rapid detection of malathion. The working principle of these biosensors is based on the irreversible inhibition of AChE enzyme activity by malathion [9]. He et al. achieved highly sensitive detection of malathion by immobilizing acetylcholinesterase on a novel core-shell nanocomposite composed of hollow carbon spheres covered with needle-like polyaniline (HCS@PANI). Specifically, after the synthesis of HCS@PANI, acetylcholinesterase was adsorbed onto this nanocomposite. When malathion is present, the electrocatalytic reaction of acetylthiocholine chloride (ATCl) by the AChE/HCS@PANI biosensor is inhibited, and this phenomenon can be used to identify the presence of malathion. By combining this nanocomposite material platform with AChE, the biosensor achieved an extremely low detection limit of 0.16 pg/mL and demonstrated excellent linear response within the range of 1.0 ng/mL to 10 μg/mL. Research indicates that HCS@PANI not only possesses a high specific surface area and outstanding chemical functionality but also significantly enhances electrochemical performance. Moreover, HCS@PANI, as an ideal immobilization layer, can effectively fix AChE and enhance its catalytic effect on ATCl, showing great application potential in highly sensitive pesticide detection [10].

3.1.3. Organic Nitrogen Compounds

Turemis et al. [11] evaluated an optical sensor based on algal bio-media for monitoring related marine pollutants. For this purpose, a symbiotic strain of algae and protozoa (green algae Chlorella vulgaris and ciliate Tetrahymena pyriformis) was tested as the bio-media, which has higher resistance to marine salinity than wild algae. The symbiotic strain was encapsulated in a flow-through cell and detected by fluorescence decay, responding to the presence of herbicides (simazine, atrazine, and diuron). A photodetector based on quantum dot nanoparticles functionalized with artificial peptides mimicking the D1 protein in the photosystem II of green algae was developed for monitoring herbicides of agricultural origin in wastewater [12]. Computational modeling, synthesis, and characterization by fluorescence spectroscopy and circular dichroism spectroscopy were carried out for the biomimetic 50 and 70-mer peptides. The molecule with the best performance in terms of structural stability and sensitivity to the herbicide atrazine was immobilized on the quantum dots, and analytical parameters, including detection limit, linear concentration range, interference studies, and matrix effects, were optimized.

3.2. Detection of Heavy Metal Ions

Heavy metals such as lead, mercury, and cadmium are significant environmental pollutants that pose a considerable threat to both humans and ecosystems. Various analytical methods, including atomic absorption spectrometry, inductively coupled plasma mass spectrometry (ICP-MS), capillary electrophoresis, and X-ray fluorescence spectroscopy, have been used to identify heavy metal ions [13]. However, these techniques are time-consuming and require complex and expensive equipment as well as well-trained personnel to perform the operation procedures.

Research on sensors based on Hg2+ is extensive. Lai et al. [14] successfully developed a novel highly selective electrochemical biosensor based on differential pulse voltammetry (DPV) for the detection of mercury ions (Hg^{2+}) in aqueous solutions. The sensor design is based on the strong specific binding between mercury ions and two DNA thymine bases (T-Hg^{2+}-T). Heme acts as a redox indicator, generating a readable electrochemical signal. The results showed a good linear relationship between signal intensity and mercury ion concentration within the range of 0 to 2 millimoles (R^2 = 0.9983), with a detection limit of 50 nanomoles. Additionally, the length of the probe DNA had a minor impact on the sensor performance. Yang et al. [13] prepared an electrochemical nanobiosensor for detecting Hg2+ in aqueous solutions using a three-dimensional graphene oxide 3D-rGO/polyaniline PANI composite material as the sensitive layer for DNA adsorption. The 3D-rGO/PANI, rich in amino groups, was immobilized on the electrode surface and tended to bind with Hg2+, forming T-Hg2+-T coordination. The sensor exhibited high sensitivity and selectivity for Hg2+ within the concentration range of 0.1 nM to 100 nM, with a LOD of 0.035 nM. In DNA-based electrochemical biosensors, buffer solutions may seriously interfere with the reaction, which is a drawback of electrochemical DNA biosensors [15].

3.3. Detection of Microorganisms

Antonacci et al. [16] developed an electrochemical biosensor for detecting bacteria in wastewater to assess overall biological toxicity. The sensor utilized cells of the green photosynthetic alga Chlorella and immobilized them on a carbon black (CB) nano-modified screen-printed electrode, with Escherichia coli as the case study. The biosensing principle is based on the interaction between bacteria and algae. When the bacteria increase, they alter the oxygen level in the microenvironment of the algae, causing the algae to overproduce oxygen and thereby increase the current signal. This effect was quantified through an amperometric transduction system because the algae's response to light enhanced the current output. This biosensor performed well in evaluating the overall biological toxicity of wastewater treatment plant effluent.

3.4. Assessment of Biological Toxicity

McNamee et al. [17] developed a multiplex surface plasmon resonance (SPR) biosensor method and analyzed seawater samples from different sampling points in Europe using a rapid sample preparation procedure. The detection limits for PSP, okadaic acid, and domoic acid toxins were determined to be 0.82 ng/mL, 0.36 ng/mL, and 1.66 ng/mL, respectively. The results demonstrated that multiplex analysis techniques have potential in marine biotoxin detection, capable of analyzing 24 samples within 7 hours and providing results. Talamini et al. [18] introduced a new direct electrochemical nano-immunosensor for detecting microcystin-LR (MC-LR). The electrochemical behavior of the immunosensor was studied by square wave voltammetry (SWV) and electrochemical impedance spectroscopy (EIS). It had a detection limit (LOD) of 0.05 ng/mL, showed a linear response in the range of 0.05 - 500.00 ng/mL, and had a response time of approximately 15 minutes, making it suitable for field investigations.

4. Challenges and Prospectives of Biosensor Application

4.1. Challenges

Marine sensors face multiple challenges in adapting to the complex and variable marine environment. Firstly, the significant fluctuations in temperature, salinity, and other physical and chemical properties of seawater make it difficult for sensors to maintain accuracy, stability, and repeatability under different conditions. In addition, sensor materials need to improve in terms of corrosion resistance, pressure resistance, and adaptability to extreme temperatures, particularly given the corrosive effects and microbial contamination in seawater. While microfluidic technology helps miniaturize sensors and reduce power consumption, it still faces technical limitations. Furthermore, biofouling poses a significant issue, as the attachment of algae and shellfish can lead to measurement errors and physical damage to the sensors. The durability and reliability of sensors also need to be enhanced to withstand extreme conditions such as strong currents, storms, and biological erosion, while cost remains a barrier to large-scale deployment. To meet the diverse needs of marine monitoring, future sensors must be intelligent and multifunctional, capable of stable operation in various environments, and capable of using machine learning and artificial intelligence to analyze vast amounts of data.

4.2. Prospectives

The development of advanced marine sensors requires overcoming significant challenges in materials science, chemistry, and electronics to meet the complex and dynamic demands of the marine environment. This includes enhancing sensor durability, accuracy, and energy efficiency, while addressing issues such as biofouling and the need for miniaturization. From the perspective of materials science, the development of new corrosion-resistant, high-pressure-resistant, and high-low temperature-resistant sensor materials is crucial; in the field of chemistry, optimizing the chemical reaction mechanism of sensors and improving their detection sensitivity and selectivity for various substances in the ocean is key; and in electronics, it is necessary to continuously enhance the signal processing capability, data transmission efficiency, and energy utilization efficiency of sensors. Only by deeply integrating materials science, chemistry, and electronics can the overall quality of sensors be optimized to meet the strict requirements of marine environment monitoring.

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The goal of maritime sensor and biosensor research should be to create small, intelligent platforms that can automatically gather, analyse, and transmit data. These platforms must be able to function in a variety of marine circumstances, including shallow waters and deep-sea locations with extreme pressures and temperatures, and be portable enough to be deployed in a variety of settings, from tiny research vessels to temporary nearshore stations. To survive extreme circumstances including powerful currents, hurricanes, and biological erosion, durability is crucial. Additionally, these platforms should also be affordable for broad use and customised for particular purposes including climate, seawater quality, and marine biodiversity monitoring. In order to effectively collect and analyse vast amounts of intricate marine data and provide more precise and predictive insights, machine learning and artificial intelligence must be integrated. In the end, this will improve the sustainability and effectiveness of maritime environmental monitoring by offering strong support for marine scientific research and resource management.

5. Conclusion

In the context of numerous challenges facing the global marine ecosystem today, the detection of marine pollutants has become a crucial research field. This review focuses on marine biosensors as a key technical means and provides a comprehensive and in-depth summary and analysis of their applications in the marine field based on the target analytes of the sensors. Among them, the typical marine pollutants covered are diverse and complex, including organic pollutants. These pollutants have a wide range of sources, such as various organic hydrocarbons after oil spills, organic dyes contained in industrial wastewater discharges, and organic pesticide residues brought by agricultural non-point source pollution etc. Heavy metal ions are also key concerns, such as mercury, lead, and cadmium. They enter the marine environment through the dumping of industrial waste, the discharge of mine wastewater, and atmospheric deposition, posing a serious threat to the survival of marine organisms and the balance of marine ecosystems. In terms of microorganisms, it includes pathogenic bacteria, viruses, harmful algae, etc. Under suitable marine environmental conditions, they may rapidly reproduce, causing marine ecological disasters such as red tides, and may also affect human health through the food chain. Biological toxicity reflects the toxic effects of various pollutants in the marine environment on organisms.

Different types of biosensors, through their unique detection principles and methods, have demonstrated outstanding detection performance for various marine pollutants, fully demonstrating their effectiveness and practicality in marine pollution detection. They provide a strong technical guarantee for marine environmental monitoring, marine ecological protection, and the sustainable utilization of marine resources. They have broad application prospects and development potential in future marine scientific research and marine environmental protection endeavors and are expected to become an important tool for safeguarding the health of marine ecosystems and promoting the development process of harmonious coexistence between humans and the ocean.

However, this study makes extensive use of secondary data, which could not fully reflect the most recent developments in biosensor technology or the real-world difficulties encountered in practical applications. More empirical studies that evaluate the practical efficacy of marine biosensors in diverse maritime habitats are required for future research. Field testing in a variety of settings, including different salinities, temperatures, and pollutant concentrations, would yield important information about the accuracy, durability, and dependability of sensors.

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