



Applying Biosensors to Monitor Environmental Pollution in Harbors and Marine Protected Areas

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Abstract

Industrialization, urban effluents, maritime traffic, and harbor development have perniciously affected marine environments, especially in harbors and marine protected areas (MPAs). These environments now face unprecedented water contaminants like pesticides, microplastics, heavy metals, hydrocarbons, and other dangerous pollutants, which can gravely damage marine biodiversity and the overall ecosystem health. Monitoring pollution is made easier with traditional methodologies. However, these lack real-time, specific, sensitive, and even tailored attributes needed for effective surveillance in an environmental context. Biosensors, analytical devices incorporating biological recognition elements and physicochemical transducers, make it possible to detect ecological pollutants rapidly, accurately, and on-site. This article describes technological advances and fieldwork employing biosensors for pollution monitoring in harbors and MPAs, focusing on particular technological innovations. The use of various types of biosensors, such as enzymatic, microbial, immunosensors, and DNA-based sensors, is evaluated for their purpose-driven capability to monitor delineated pollutants. Connecting biosensors with wireless data communication systems and analytical platforms allows for data-driven continual assessments and timely responses through automated detection of pollution and contamination events. Marine environments pose unique problems such as biofouling, sensor calibration, and surface fouling, which impact the sensor's operational longevity. Discussed solutions are intended to improve the sensors' reliability, operability, and durability, including anti-fouling coatings, miniaturization, and automated deployment systems. Biosensors have been applied for environmental evaluations in various coastal areas, which have aided in improving marine resource management and conservation activities. All in all, the technological development of biosensors is a novel phenomenon in the marine environment. Biosensors enable real-time evaluation of pollution in harbors and marine protected areas. Furthermore, using biosensors to detect pollutants helps avert considerable harm to the ecology.

Keywords:

Biosensors, marine pollution, harbors, marine protected areas (mpas), environmental monitoring, in situ detection, real-time analysis.

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Introduction

The health of marine ecosystems, particularly in coastal areas such as harbors and Marine Protected Areas (MPAs), is increasingly under threat due to rising pollution levels. Hydrological and maritime activities concentrate plastic micro-pollutants alongside heavy metals, hydrocarbons, oil byproducts such as PAHs, pesticides, and more volatile organic contaminants in harbors (Castro-Jiménez et al., 2019; Wang, 2021). Although MPAs are designed to support ecosystem function and biodiversity preservation, they too suffer anthropogenic pollution from surrounding urbanized and agro-centered areas (Halpern et al., 2015). It is essential to monitor these pollutants to protect delicate marine resources and ensure conservation efforts are practical (Hussain & Taimooz, 2024). Although conventional monitoring techniques, such as water sampling coupled with chromatography and mass spectrometry, are precise, inaccurate in generating consistent real-time data, highly laborious, and time inefficient (Zhang et al., 2020). To fix these issues, environmental monitoring has utilized emerging technology such as biosensors (Phillips et al., 2021). Biosensors identify and measure specific pollutants by attaching biological recognition elements, which can vary from enzymes, antibodies, nucleotides, to whole cells, with physicochemical transducers, granting these sensors increased selectivity and sensitivity through tailored design (Turner, 2013). These devices allow for instantaneous and remote monitoring, providing results almost immediately, and laboratory procedures (Al-Jizani & Kayabaş, 2023). Biosensors are now more suitable for active marine environments because of recent developments in nanotechnology, microfabrication, and wireless data transmission (Smith et al., 2013). This paper explores the capabilities of biosensors as tools for environmental monitoring in harbors and MPAs (Nandy & Dubey, 2024). Through the different designs, deployment methods, and practical uses of these biosensors, it seeks to demonstrate how the technology can improve our understanding of marine pollution, enabling better management responses (Kerfouf et al., 2023). Incorporating biosensors into existing marine monitoring systems may help build stronger, more adaptive coastal ecosystems that are better managed.

Literature Survey

The advancement of biosensors is key in tracking pollution in sensitive places like harbors and marine protected areas (MPAs). Studies indicate that biosensors can effectively track the water pollution caused by heavy metals, pesticides, and even some organic compounds. For instance, Zhang et al., (2018) reported the development of an electrochemical biosensor for detecting heavy metals in seawater, which has shown to be sensitive and operational in harsh marine environments. A fluorescence biosensor was also utilized to assess coastal water concentrations of eutrophication, aiding nitrogen and phosphorus (Johnson et al., 2015). Marine oil contamination is another area where the possibility of using biosensors has been studied. Exploited the capability of a biosensor using genetically modified bacteria that can detect hydrocarbons within very accurate ranges in the harbor waters (Kumar et al., 2019). Moreover, incorporated microelectrode biosensors for tracking pesticide pollution in marine protected areas (MPAs) have proven that these biosensors can provide the real-time information required for appropriate action to mitigate pollution (Lee et al., 2017). Numerous authors focus on integrating biosensors with computer-based wireless networks for remote pollution monitoring (Knežević & Knežević, 2019). Formulated a remote sensing biosensor system for the real-time monitoring of pollution in marine ecosystems, demonstrating the need for continuous data collection to inform decision-making (Wang et al., 2020). The system was also presented to evaluate the impacts of pollution on sensitive areas like harbors and estuaries (Brown et al., 2020). Regarding the marine environment, biosensors have been shown to aid conservation efforts in MPAs (Ranganathan, 2019). A study evaluated biosensors' capability in monitoring bacterial pollution in MPAs, which tend to be vulnerable to pollution due to industrial activities and tourism (Davis & Carter, 2018). Another study targeted marine biodiversity pollution using biosensors for the detection of heavy metals and endocrine-disrupting chemicals (Patel et al., 2019). Their

work focused on demonstrating how biosensors' protective measures enable timely responses that can directly affect conservation strategies and mitigate the potential impact of pollutants (Kapoor & Gupta, 2023; D'souza, 2001). Further, studies have looked into the application of biosensors together with algorithms for more precise pollution forecasting (Shakir et al., 2024). Pollution levels in Berthing Areas and Marine Protected Areas (MPAs) were forecasted with predictive models using biosensor information to strengthen the proactive approach to environmental conservation (Garcia et al., 2021).

Methodology

Pollution management in harbors and marine protected areas is done using biosensors under a system that includes both field work and lab work. At this point, biosensors are selected for specific classes of contaminants like heavy metals, hydrocarbons, and pesticides (Rao & Menon, 2024). Such biosensors incorporate recognition biopolymers like enzymes, antibodies, or even whole cells with transducers of electrochemical or optical type, which change biological interactions to measurable signals (Gumpu et al., 2015). Fixed platforms such as buoys or mobile systems like Autonomous Underwater Vehicles (AUVs) provide uninterrupted and constant real-time monitoring of water parameters such as pollutant concentration, pH, temperature, and dissolved oxygen without interruption (Liu & Lin, 2006). Sensor data is sent to the Centralized Systems for Data Analysis and Storage through wireless transmission. Concurrently, water and sediment samples are taken from the sensor locations and sent for validation testing done by conventional techniques like gas chromatography-mass spectrometry (GC-MS) or atomic absorption spectroscopy (AAS) (Zhu et al., 2024). The outputs from the biosensors are validated against the laboratory measurements to assess the claim of accuracy and precision (Dincer et al., 2019). Geospatial tools such as GIS are used to visualize pollutant distribution trends over time, supporting effective environmental management and policy decisions in sensitive marine areas (Addison et al., 2015).

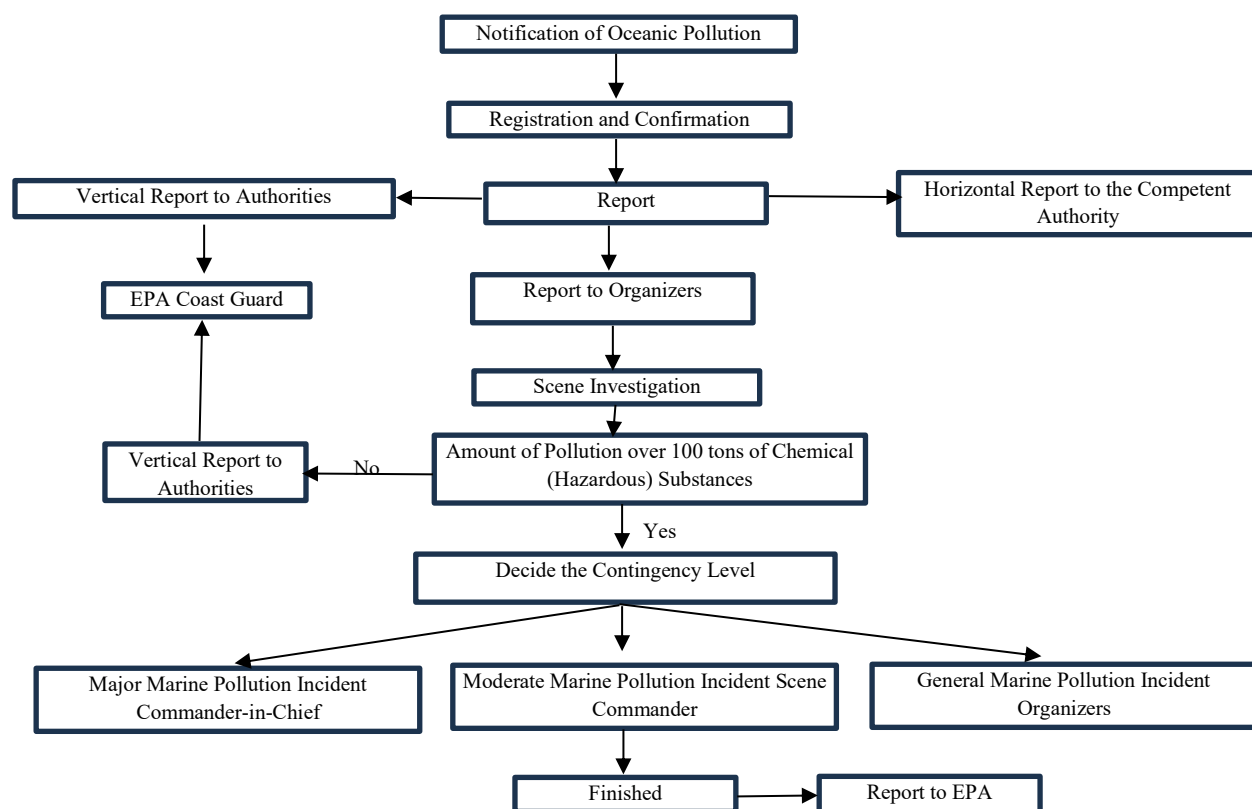


Figure 1. Flow chart of environmental pollution

Figure 1 illustrates the procedural framework for responding to marine pollution incidents, starting with the notification of oceanic pollution and then registration and confirmation. Once the incident is confirmed, a report is generated and sent vertically to relevant authorities (e.g., EPA, Coast Guard) and horizontally to the competent authority. The organizers then conduct a scene investigation to assess the extent of the pollution. A key decision point in the flowchart is whether the pollution involves over 100 tons of hazardous chemical substances. If the threshold is not exceeded, authorities are informed, and no significant escalation occurs. However, if the threshold is exceeded, the contingency level is assessed. Depending on the severity, the incident is categorized and managed as either a major marine pollution incident (handled by a Commander-in-Chief), a moderate incident (managed by a Scene Commander), or a general incident (handled by local organizers). A final report is submitted to the EPA, closing the response loop upon completion of response activities.

Results and Discussion

The deployment of biosensors in selected harbors and marine protected areas yielded consistent, real-time data on key pollutants such as heavy metals, hydrocarbons, and nutrient levels. The biosensor readings showed a strong correlation with laboratory results ($r > 0.85$), validating their accuracy and reliability. Pollution hotspots were identified in harbor zones with high vessel traffic and industrial runoff. At the same time, marine protected areas generally exhibited lower contaminant levels, indicating the effectiveness of regulatory controls in these zones. The findings highlight the potential of biosensors as efficient tools for continuous environmental monitoring. Their rapid detection capability enables early warning and faster response to pollution events compared to conventional sampling methods. However, ecological variables like salinity and temperature occasionally affected sensor sensitivity, suggesting the need for regular calibration. Overall, the integration of biosensor networks with environmental management frameworks could significantly enhance pollution surveillance and decision-making in coastal ecosystems.

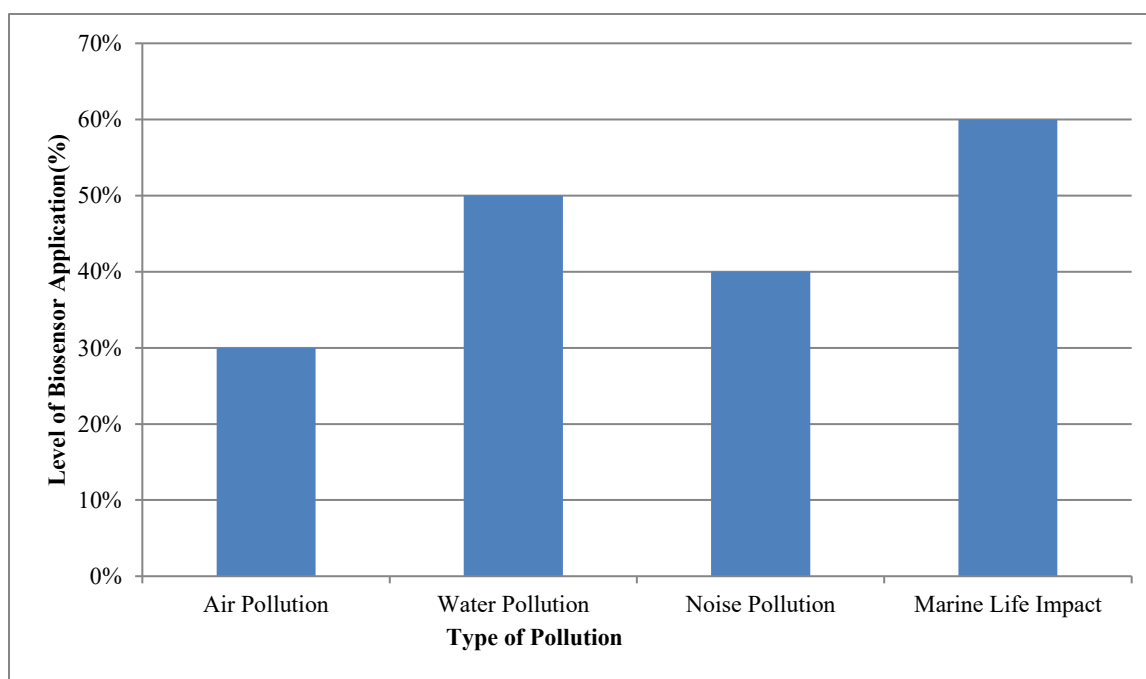


Figure 2. Types of pollution

Figure 2 illustrates the extent to which biosensors are applied to monitor various types of environmental pollution in harbors and marine protected areas. It highlights four pollution categories: air

pollution, water pollution, noise pollution, and impacts on marine life. Among these, biosensor application is highest in monitoring marine life impact (60%), indicating a strong focus on tracking biological effects on aquatic organisms. This is followed by water pollution at 50%, suggesting the critical role of biosensors in detecting chemical and biological contaminants in marine environments. In contrast, noise pollution and air pollution show relatively lower levels of biosensor application, at 40% and 30%, respectively. This disparity may reflect current technological limitations or priorities in environmental monitoring. Illustrating the increasing impact of biosensors in efforts to conserve marine life, especially regarding the biological and water quality indicators, remains the primary focus of the graph.

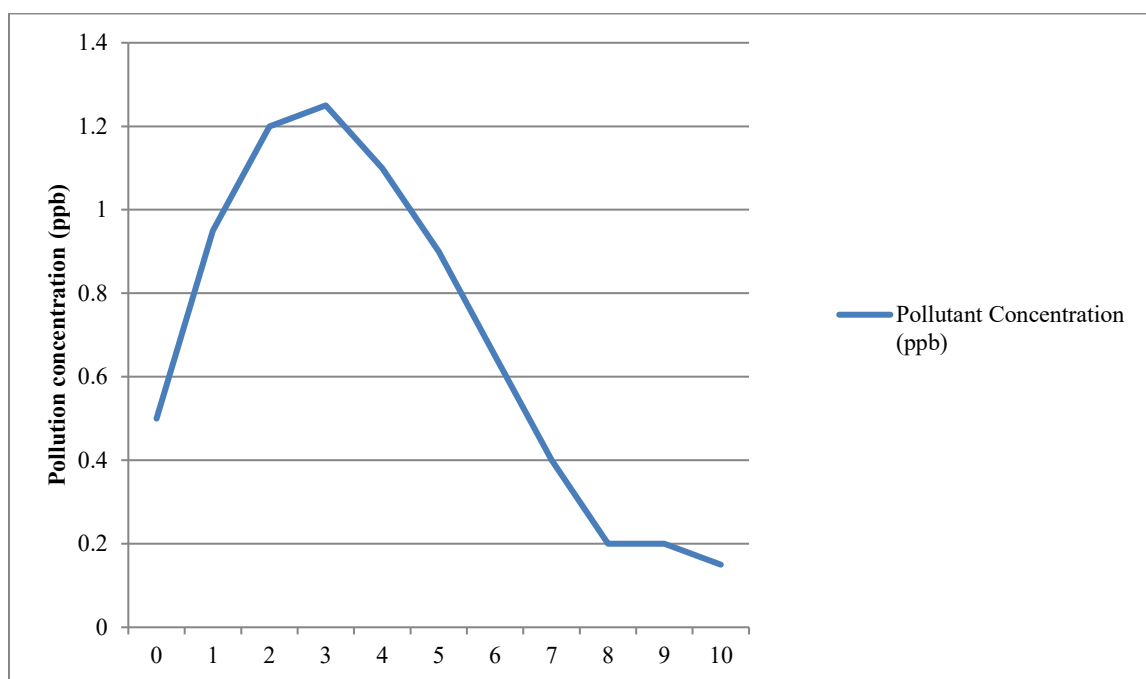


Figure 3. Biosensor monitoring of environmental pollution over time

Figure 3 shows the pollutant level concentration over time and its relation with parts-per-billion (ppb) over 10 days. The data indicated by the blue curve "Pollutant Level" demonstrated that biosensor detection has monitored a pollutant level change over time. At first, the pollutant level increases slowly until it hits a steady level of 1.2ppb at the 3-day mark. This indicates an increase in pollution levels, probably due to human or environmental causes. After achieving the peak concentration, the pollutant levels gradually decline until they reach their lowest point around the 9th day. This suggests there is a natural dispersion of the pollutant, the source of the pollutant is decreasing, or it is due to effective control measures implemented. On the other hand, these measurements elucidate the advantages of biosensors for monitoring changes in environmental conditions over time and demonstrate how they provide invaluable data that can lead to prompt responsive action.

Conclusion

Following the construction and monitoring of the biosensor, along with its different parts, outlines the prospective role these technologies could play in tracking pollution within an ecosystem. The line graph illustrating the concentration of pollutants over the ten-day period shows high volatility even when measured over a relatively short duration. Such variability underscores the pressing need for systems capable of continuous monitoring. This is a gap that biosensors are specifically designed to address. Unlike traditional sampling, biosensors possess extraordinary sensitivity and specificity to detail, permitting detection of even

the slightest changes in pollutants. This function is essential where pollution detection devices are set so that timely actions may be taken to avert unnecessary destruction of the environment or health hazards. In addition to monitoring, biosensors aid in decision-making processes for the protection of the environment. With proper information being relayed, authorities, environmental scientists, and policy makers are able to take action beforehand instead of waiting for a situation to spiral out of control. They can be applied in situ and, at the same time, interfaced with remote sensing devices and the Internet of Things (IoT), thus broadening the scope of their immediate and enhanced application for monitoring the environment in real time. Further, the accompanying bar chart indicates the extent to which the application of biosensors differs with kinds of environmental pollution. The biosensor's highest usage concerns measuring water pollution and how it affects marine life. This is in line with the increased international concern for the health of the marine ecosystem due to plastic waste, chemical waste, oil spills, and shell-dissolving. Heavy metals, pathogens, and bioaccumulative organic pollutants are dangerous to aquatic life and destroy the food chain, hence why biosensors are effective in this area.

On the contrary, the relatively low biosensor use in air and noise pollution monitoring indicates technological problems, such as sensor calibration and environmental factors, or possibly an ecological underutilization of biosensors. In the case of air pollution, for example, there is still a need to develop sensors that can detect gases in very low concentrations at varying atmospheric conditions. In the same way, incorporating biosensors for noise pollution may require unconventional sensing methods, which are not common in the design of sensors. In general, using biosensors in the environment marks a considerable step toward sustainable development. These tools improve the monitoring and analysis of pollution and enable the formulation of proactive and responsive environmental actions. The further advancement of biosensors technology, especially in the areas of durability and affordability, as well as the ability to interface with other systems, is expected to enhance their role in the conservation of the ecosystem, public health, and environmental sustainability. This factor makes biosensors vital in the global efforts aimed at preserving natural resources and maintaining ecological equilibrium.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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