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Microbial Biosensor - A Tool for Monitoring Environmental Pollutants

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ABSTRACT

The environmental quality of water, soil, and air is increasingly degraded, making it essential to enhance pollution prevention through environmental monitoring. Several methods exist for monitoring environmental quality, with a particular focus on biological approaches. Biological methods evaluate environmental health by analyzing the presence of diverse species, such as bacteria, virus, insects, plants, and fish, as indicators. Microbial biosensors are capable of detecting substances in the environment due to the specific biological reactions of microorganisms or their components. The growing emphasis on sustainable development and environmental conservation has fuelled interest in biomonitoring as a proactive approach to managing pollution. Furthermore, technologies such as bioinformatics and genetic engineering enable the way for designing highly sophisticated and efficient microbial biosensors capable of detecting environmental pollutants with greater precision and sensitivity.

INTRODUCTION

Environmental pollution has become one of the most pressing global issues, with global warming - driven by greenhouse gas (GHG) emissions - serving as a primary indicator of the environmental crisis. In response, over 100 countries have implemented restrictions on GHG emissions. However, effective management of environmental health requires more than just regulations; it necessitates comprehensive monitoring of ecosystems and pollutants contaminating our air, water, food, and soil. These pollutants pose significant ecological risks, making it imperative to identify their sources, understand their impacts, and develop strategies to mitigate their presence.

In an era of rapid industrialization and urbanization, pollution levels have escalated dramatically. Traditional methods of pollution monitoring typically rely on complex, expensive equipment and time-consuming chemical analyses that demand extensive expertise. In contrast, microbial biosensors - biological tools utilizing microorganisms to detect environmental contaminants, offer an innovative, cost-effective, and sustainable alternative. These biosensors present a promising solution to pollution monitoring by harnessing the natural capabilities of microorganisms to identify pollutants and generate measurable responses.

Microbial biosensors have gained increasing attention for their applications across environmental monitoring, food safety, and biomedical fields. Microorganisms such as bacteria, yeast, and algae are particularly well-suited for biosensor development due to their ability to be mass-produced, their ease of manipulation, and their stability *in vitro* (Wilson & Gifford, 2005). These advantages simplify the fabrication of biosensors and enhance their overall performance, making them an ideal tool for tackling environmental pollution challenges.

MICROBIAL BIOSENSORS

Microbial biosensors are analytical devices that integrate microorganisms or their biological components—such as enzymes, proteins, or whole cells-into a transducer system. The biological recognition element of the biosensor interacts with the target pollutant, triggering a specific biological response. The transducer then converts this response into a detectable signal, which can be measured through various techniques, including electrochemical, optical, acoustic, mechanical, calorimetric, or electronic methods (Paul et al., 2024). The signal is directly correlated with the analyte concentration, providing valuable data on the presence and levels of contaminants as represented in figure 1.

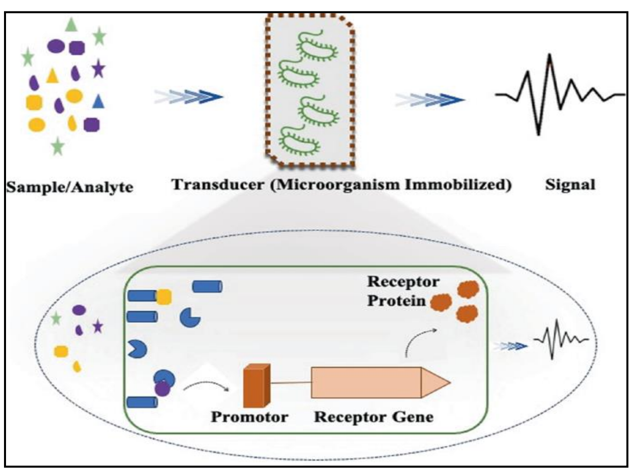

Figure 1. Schematic Representation of Microbial Biosensor Functionality

(Image source: Paul *et al.,* 2024)

TYPES OF MICROBIAL BIOSENSORS:

1. WHOLE-CELL-BASED MICROBIAL BIOSENSORS (WCBMB)

Whole-cell-based microbial biosensors utilize intact microorganisms, often genetically modified to enhance their sensitivity to specific pollutants. These biosensors rely on the natural biological processes of the microbes, which can be engineered to produce measurable responses when they encounter target substances. For instance, certain bacteria can be designed to emit light (bioluminescence) when exposed to toxins such as heavy metals or organic pollutants. This bioluminescence can be detected and quantified, providing a straightforward and rapid method for assessing pollution levels.

Although whole-cell biosensors may not exhibit the same level of sensitivity to environmental changes as molecular-based biosensors, they offer unique advantages. By using simple genetic engineering techniques, microorganisms can be tailored to detect a wide range of pollutants and respond to complex biochemical changes within living cells. This adaptability makes whole-cell biosensors highly suitable for monitoring intricate environmental conditions. Additionally, these biosensors are robust, cost-effective, and capable of functioning across diverse environments, making them ideal for real-time, on-site pollution detection.

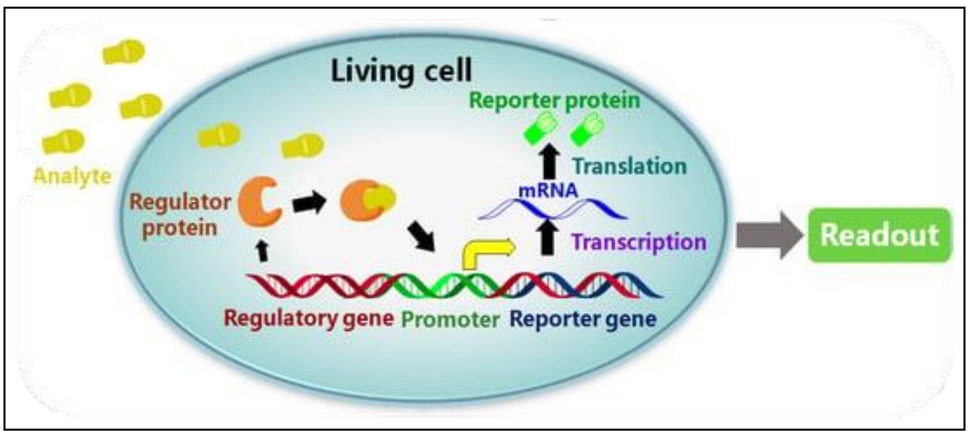

Figure 2. A schematic image representing a typical whole cell-based biosensor (Image source: Gui *et al.,* 2017)

2. ENZYME BASED BIOSENSOR

Enzyme-based microbial biosensors utilize isolated enzymes from microorganisms to detect pollutants. These enzymes catalyze specific biochemical reactions, resulting in measurable changes, such as pH shifts or the production of electrochemical signals, that can be converted into detectable outputs by a transducer. The efficiency of these biosensors depends on the stability of the enzyme under working conditions and the availability of the enzyme to catalyze the desired reaction.

Designing effective enzyme-based biosensors requires in-depth knowledge of the target analyte and an understanding of the environment in which the biosensor will operate (e.g., water, soil, or biological fluids). These biosensors are particularly useful for detecting organic pollutants and other substances that can be readily metabolized by the enzyme.

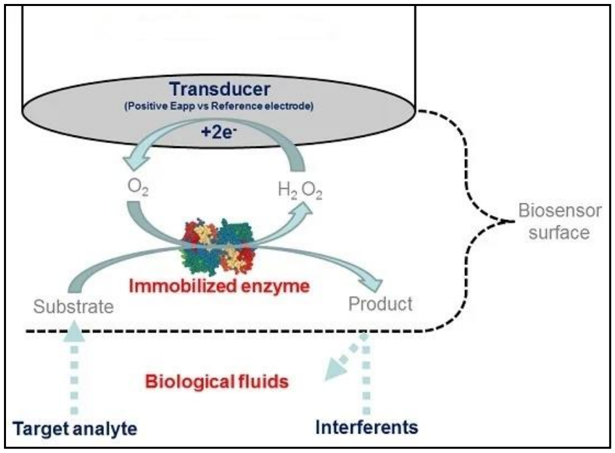

Figure 3. Schematic image representing a typical enzyme based biosensors

(Image source: Rocchitta *et al.,* 2016)

3. DNA-BASED MICROBIAL BIOSENSOR

DNA-based microbial biosensors are highly versatile tools used to detect pollutants by assessing their impact on microbial DNA or RNA. When pollutants interact with microbial cells, they can induce alterations in gene expression or cause DNA damage. DNA-based biosensors measure these changes, correlating them with the presence and concentration of specific contaminants.

One of the significant advantages of DNA-based biosensors is their specificity. They can be engineered to target specific DNA or RNA sequences, enabling precise detection of pollutants such as heavy metals, pesticides, and organic compounds. These biosensors can even detect low concentrations of pollutants, providing early warnings of contamination. In environmental monitoring, they offer a powerful tool for identifying trace contaminants in biological samples, contributing to environmental and public health safety.

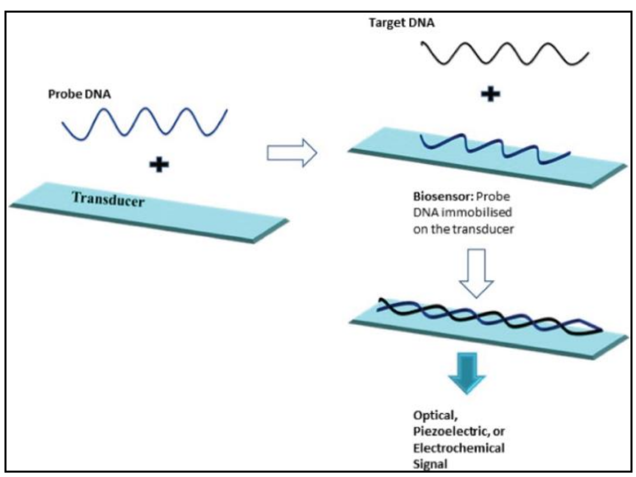

Figure 4. Schematic Illustration of DNA Hybridization Biosensors

(Image source: Hamed *et al.,* 2020)

APPLICATIONS OF MICROBIAL BIOSENSORS

Microbial biosensors have a wide range of applications in environmental monitoring, food safety, and industrial processes. Unlike traditional chemical methods, which are often complex and costly, microbial biosensors provide a more accessible and cost-efficient solution. Some of the key applications of microbial biosensors are outlined in Table 1.

Table 1. Applications of Microbial Biosensors for Industries and Environmental Monitoring

Analyte Type	Microorganism(s) Used	Applications
Carbohydrates	*Pseudomonas fluorescens*, *Gluconobacter oxydans*, *Escherichia coli*	Biotechnology, food industry, medicine
Alcohols	*Hansenula polymorpha*, *Aspergillus niger*, *Acetobacter aceti*	Monitoring ethanol in beverages, biotechnological processes
Organic Acids	*Hansenula anomala*, *Arthrobacter nicotianae*	Blood lactate analysis, detection of fatty acids
BOD (Biological Oxygen Demand)	*Trichosporon cutaneum*, *Escherichia coli*, active sludge	Environmental monitoring, water quality assessment
Surfactants (SAS)	*Pseudomonas rathonis*, activated sludge bacteria	Detection of detergents in water bodies
Pesticides	*Escherichia coli* (recombinant), *Pseudomonas putida*	Detection of organophosphorus pesticides
Hydrocarbons and Derivatives	*Rhodococcus erythropolis*, *Pseudomonas fluorescens*	Detection of benzene, naphthalene, Polycyclic Aromatic Hydrocarbons in water
General Environmental Pollutants	*Sphingomonas sp.*	Real-time monitoring of pollutants, toxicity assays

FUTURE INNOVATIONS AND CONCLUSION

Advancements in synthetic biology and nanotechnology are set to enhance microbial biosensors, enabling more efficient and portable solutions for environmental monitoring. With the integration of microfluidic systems and wireless technologies, these biosensors could be linked to smartphones for real-time data collection. Furthermore, the development of multi-analyte biosensors will enable the simultaneous detection of multiple pollutants, increasing the versatility and utility of microbial biosensors in various applications. Microbial biosensors represent a powerful convergence of biological sensitivity and technological innovation. As research progresses, these biosensors will play a crucial role in addressing environmental pollution, providing sustainable and cost-effective solutions to monitor and protect our air, water, and soil for future generations.

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