NEXT-GEN SOIL MONITORING: BIOSENSORS TO MONITOR SOIL HEALTH OR TOXICITY

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Human existence, as well as the vitality of other organisms, is largely contingent upon the health of soil. Soil serves as a crucial fundamental component for human sustenance, intimately intertwined with public well-being. Notably, many vital trace elements essential for human health originate from soil. Soil contamination due to the introduction of anthropogenic substances or alterations to the soil environment results in pollution of soil and water bodies.

Various detrimental elements contaminate soils include industrial waste, disease-causing bacteria, heavy metals like arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn), pesticides like organophosphates (OPP) and organochlorines (OCPs) such as dichloro-diphenyl-trichloroethane and hexachlorocyclohexane, herbicides, and polycyclic aromatic hydrocarbons derived from industrial processes like naphthalene, phenanthrene, or benzo[a]pyrene. These contaminants infiltrate the soil environment, presenting significant risks to human health and the natural ecosystem. The consequent effects of these changes on soil health leads to the decline in agricultural productivity and related losses.

TRADITIONAL APPROACHES OF EVALUATING SOIL CONTAMINANTS

Traditionally, soil contaminant analysis is being carried out using approaches like gas chromatography, high-performance liquid chromatography, atomic absorption spectroscopy, inductively coupled plasma-atomic emission/mass spectroscopy, and nitrogen-phosphorus or flame-photometric detection.

BIOSENSORS AND COMPONENTS

Biosensors are devices leveraging specific biochemical reactions facilitated through isolated enzymes, immune systems, tissues, organelles, or whole cells to detect chemical compounds through electrical, thermal, or optical signals (Figure 1). Within biosensors, a biological component viz., an enzyme, antibody, microbe/tissue, or nucleic acid interacts with the analyte, inducing a physical or chemical alteration (Figure 2). This alteration is then detected by the transducer, which converts it into an electrical signal. Subsequently, this signal is interpreted to detect the analyte concentration within the sample. A transducer functions as a device capable of converting radiation or physical quantities like pressure or brightness into an electrical signal, or vice versa.

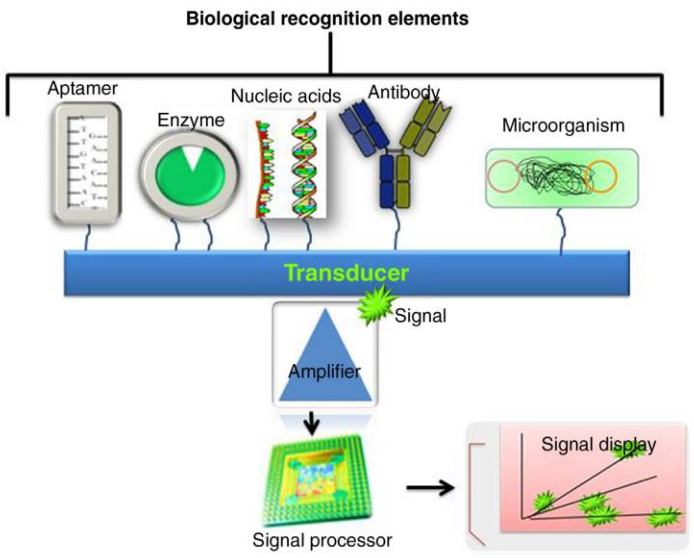

Figure 1. Schematic diagram of Biosensors (Source: Rajkumar et al., 2017)

Analyte refers to the substance targeted for detection, encompassing molecules such as proteins, toxins, peptides, vitamins, sugars, and metal ions. **Biological elements**, including antibodies, enzymes, cells, and polymers, interact with the analyte and convey alterations in its composition as a signal. The **transducer** serves as a physical component that enhances the biochemical signal acquired from the detector, transforming the resultant signal into electrical form and presenting it in an accessible manner. The **electrical circuit** comprises components such as the Signal Conditioning Unit, a Processor or Micro-controller, and a Display Unit, collectively facilitating signal processing and presentation.

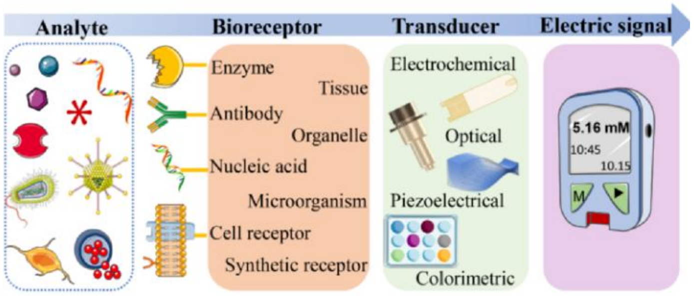

Figure 2. Componets of Biosensors (Source: Meng, 2020)

TYPES OF BIOSENSORS

Biosensors are categorized based on their biological element or bioreceptor, which includes enzyme-based, microbial, and antibody-based biosensors. Enzyme biosensors leverage their catalytic activity and binding properties to achieve specific detection, as seen in glucose sensors. Microbial biosensors utilize microorganisms such as bacteria and fungi to detect specific molecules or assess overall environmental condition, utilizing indicators like cell metabolism, viability, respiration, and bio-luminescence. For instance, *Rhodococcus erythropolis* can be employed to measure biochemical oxygen demand (BOD). Antibody-based biosensors capitalize on the high specificity between antibodies and antigens. For the detection of binding events methods like fluorescent labelling or observation of the changes in refractive index or reflectivity can be used. Antibody-based biosensors are commonly used for the detection of polychlorinated biphenyls (PCBs) such as nonbiodegradable chemical insecticides and herbicides.

ELECTROCHEMICAL BIOSENSORS

Electrochemical biosensors often rely on the enzymatic catalysis to initiate reactions that either generate or consume electrons. The resultant reporter signal is assessed through electrochemical reactions. This methodology enables the assessment of bacterial metabolic activity through the analysis of electrical parameters derived from impedance spectra, which are fitted using an equivalent electrical circuit. Amperometric microbial biosensors used in the detection of pathogenic microorganism, organophosphate pesticides, cyanide, heavy metals and pollutants such as Cd, Pb, Hg, Zn and Cu. Amperometric monooxygenase biosensors detect aromatic hydrocarbons like phenols and catechol.

Potentiometric microbial biosensors are utilized to detect environmental pollutants. Urea-detecting potentiometric biosensor functions as an enzyme-based system. Conductometric microbial biosensors are designed for the detection and identification of environmental contaminants, including pesticides. Specifically, the conductometric biosensor has been utilized to identify the pesticide methyl parathion (O, O-dimethyl O-4-nitrophenyl phosphorothioate).

OPTICAL MICROBIAL BIOSENSORS

An optical biosensor is a device that utilizes an optical transducer to induce changes in various optical properties corresponding to the analyte concentration. Microorganisms capable of detecting analytes can generate optical signals directly proportional to the analyte concentration. These biosensors are crucial to identify pathogenic organisms, such as *Campylobacter* spp., as well as pesticides like metaphos and methyl parathion. Fluorescent microbial biosensors emit light proportional to the analyte concentration, even at low levels. These biosensors couple stress-responsive genes or promoters with the Green Fluorescent Protein (GFP) coding sequence, allowing for straightforward monitoring of fluorescent signals.

An *in vivo* fluorescent biosensor can autonomously produce fluorescent proteins without an external stimulation or fluorescent elements and is effectively used for detecting toxic metals. Bioluminescent microbial biosensors, based on the natural bioluminescence (refers to the visible light emitted by living organisms) of certain bacteria, are highly sensitive to various environmental contaminants, such as industrial heavy metals and pesticides. For instance, luminescent-dependent *E. coli* WCB, such as *Ralstonia metallidurans*, has been utilized to assess heavy metal content in polluted soil and environments. Colorimetric microbial biosensors detect analyte concentrations by observing changes in the colour of specific compounds. For example, methyl parathion can be hydrolyzed by bacteria into a chromophoric product that can be quantified using colorimetric methods. These indicators are effective for detecting heavy metal contamination in soil. Prussian blue has been used as a colorimetric indicator for the detection of contaminants like 3,5-dichlorophenol (DCP), arsenic (As^{3+}), and chromium (Cr^{6+}).

PROPERTIES OF A GOOD BIOSENSOR

A good biosensor exhibits several key properties. Firstly, it should demonstrate high specificity for the analyte in question, ensuring accurate detection. Additionally, its response should maintain linearity over a wide range of substrates, enhancing its versatility. The device itself should be compact and bio-compatible, facilitating ease of use and minimizing any potential adverse effects. Also, cost-effectiveness is crucial, necessitating that the biosensor be affordable, small, and straightforward to operate. Ideally, the assay cost should undercut that of conventional tests, promoting its widespread adoption. Finally, the assay process should be swift, reliable, and reproducible, ensuring consistent and timely results.

ADVANTAGES AND DISADVANTAGES

The method is straightforward and requires no sample processing. A limited number of samples suffice for the assessment due to its high sensitivity. It is economically viable and offers good accuracy. Experimental periods for assessment are short, and it is user-friendly. Additionally, it boasts a low detection limit and long-term stability, addressing the shortcomings of conventional techniques viz., time consumption, sample preparation needs, high cost, and poor selectivity. However, it cannot undergo heating sterilization as this would damage the biological component of the biosensor. Some biosensors, like calorimetric test strips, are for single use only, reducing their reusability. Moreover, complex environmental matrices may cause significant interferences during the detection of target analytes by biosensors.

CONCLUSION

Pollution has catastrophic effects on our ecosystems, severely hampering economic growth. Pollutants pose significant threats to human health and other living organisms. Biosensors play a vital role in environmental monitoring and industrial applications, contributing to biotechnology. Microbial biosensors are capable of analyzing moderately complex samples without sample enrichment, while maintaining high sensitivity and selectivity. These biosensors are cost-effective, time-efficient, and excellent for monitoring soil conditions. They are essential tools for reducing expenses and optimizing environmental monitoring. Nano biosensors are crucial in detecting pesticides and herbicides, and tracking their bioaccumulation in vegetables. Integration of nanoparticles in biosensor design have a promising future. Future research should be focused on the development of smaller, cost-effective, and flexible biosensors technologies to facilitate large-scale soil condition assessments.

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