



Microbial Biosensors for Environmental Monitoring and Sustainability

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Environmental pollution is a major challenge affecting soil, water and living organisms. Industrial activities, mining, improper waste disposal and intensive agricultural practices can introduce contaminants into the environment. These include potentially toxic elements such as cadmium, lead, mercury, arsenic, chromium and copper, as well as pesticides, hydrocarbons and other chemicals. Monitoring such contaminants is essential for protecting ecosystem health, agricultural productivity and human well being. Environmental monitoring commonly uses analytical techniques such as chromatography, atomic absorption spectroscopy and inductively coupled plasma-based methods. These techniques can provide accurate measurements, but they may require specialised instruments, sample preparation, laboratory facilities and trained personnel. Moreover, the total concentration of a contaminant does not always indicate how much is available to living organisms or the biological effects it may cause. Biosensors offer a complementary approach by combining biological recognition with a measurable output. Microbial biosensors are particularly useful because microorganisms respond to changes in their surroundings.

Microbial biosensors: living cells as sensing elements

A biosensor combines a biological recognition element with a system that converts the resulting response into a measurable signal. The recognition element may be an enzyme, antibody, nucleic acid or whole cell. The signal may be optical, electrical or another measurable output. The signal is then processed and interpreted. In microbial biosensors, microorganisms such as bacteria, fungi and algae act as the sensing element. They may respond to contaminants through changes in metabolism, respiration, enzyme activity, gene expression, growth or viability. Some systems use naturally occurring microbial responses, whereas others use genetically engineered microorganisms that produce a reporter signal, such as fluorescence or bioluminescence, when a target substance activates a specific biological pathway. Microbial biosensors have been investigated for monitoring nutrients, metals, pesticides and organic pollutants (Moraskie *et al.*, 2021). An important advantage of whole cell microbial biosensors is that they can provide information about the biologically available fraction of a contaminant. The total concentration measured in soil or water may not equal the fraction accessible to living organisms. Factors such as pH, organic matter, clay content and ionic composition can affect this availability. A microbial response can therefore complement, but does not replace, conventional chemical analysis.

How do microbial biosensors work?

The principle is straightforward: a microorganism encounters a target substance, responds to it, and generates a change that can be measured. The substance may interact with cellular components or regulatory pathways, producing a biological response. In some systems, the response is detected through changes in respiration, oxygen consumption or metabolic activity. In genetically engineered whole cell biosensors, a target responsive regulatory system may be linked to a reporter gene. The reporter can produce fluorescence, bioluminescence or another

detectable signal. Depending on the design, the signal may increase or decrease with the target concentration or its bioavailable fraction. Recombinant DNA technology and synthetic biology are helping researchers develop systems with improved sensitivity and selectivity, although performance must be validated under realistic environmental conditions (Moraskie *et al.*, 2021; Li *et al.*, 2025).

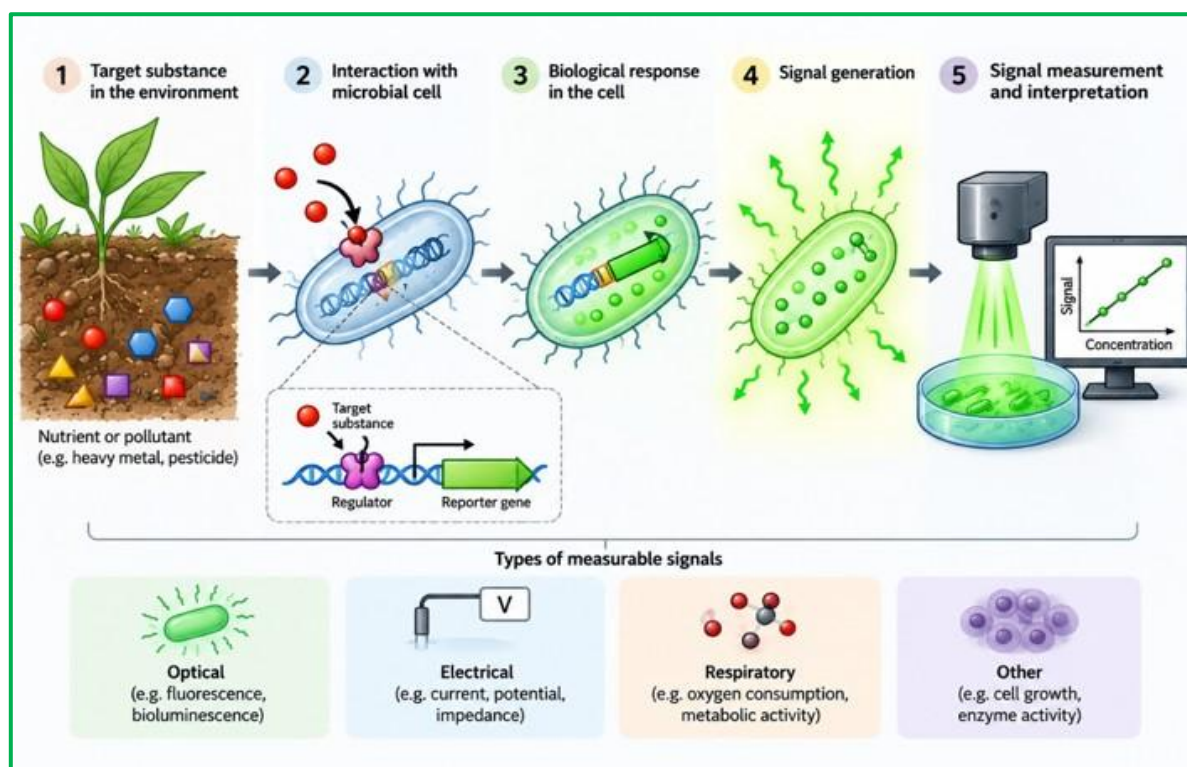


Fig.1 General principle of microbial biosensors showing target recognition, microbial response, signal generation and measurement for environmental monitoring

Microbial biosensors for soil and water monitoring

Soil is an important reservoir for many environmental contaminants. Metals, pesticides and industrial chemicals can accumulate in soil and affect microorganisms, plants and other organisms. Microbial biosensors are being explored to provide rapid information about the presence or biological effects of these contaminants. Examples of microbial systems investigated for environmental sensing are summarised in Table 1.

Table 1. Examples of microorganisms investigated for soil and environmental biosensing

Microorganism	Target or application
Sulfur oxidizing bacteria (SOB)	Monitoring heavy metal toxicity in soil
<i>Pseudomonas putida</i>	Biosensing of organophosphate pesticides
<i>Chlamydomonas reinhardtii</i>	Detection of heavy metals
<i>Ralstonia metallidurans</i>	Sensing of heavy metals
Reporter strains of <i>Escherichia coli</i>	Detection of nutrients and toxic metals

These examples illustrate the range of microbial systems studied for environmental monitoring. The response and reliability of each system depend on the organism, target substance and test conditions. Water quality is another important application. The naturally bioluminescent bacterium *Vibrio fischeri* is widely used in toxicity tests because exposure to toxic substances can reduce its light output. This response provides an integrated indication of sample toxicity rather than identifying the concentration of a single chemical. It can therefore be useful when a sample contains a mixture of contaminants. Microbial systems have also been investigated for estimating biochemical oxygen demand (BOD) and monitoring organic pollution. Such applications show that microbial biosensors can provide information about both specific pollutants and broader changes in environmental quality.

Optical microbial biosensors

Optical microbial biosensors detect changes in light or colour. Fluorescence-based systems may use a reporter protein such as green fluorescent protein (GFP). When a target responsive promoter activates the GFP gene, the cells produce fluorescence that can be measured with a suitable detector. Bioluminescent systems use light produced by naturally luminescent microorganisms or by engineered reporter systems. A change in light output may indicate toxicity or the presence of a target contaminant. Colour based systems provide another option, producing a visible change that can sometimes be read with simple equipment. These approaches are promising for portable testing, but their sensitivity and accuracy need to be assessed for the intended sample and field conditions.

Electrochemical microbial biosensors

Microbial responses can also be converted into electrical signals. Electrochemical systems measure parameters such as current, potential or impedance associated with microbial activity. In microbial bioelectronic sensors, biological processes are coupled to an electrode to generate a measurable electrical output. Researchers are exploring these systems for rapid detection of environmental toxins, monitoring pesticide degradation and developing field deployable devices. However, moving from laboratory demonstrations to robust field applications remains a challenge (Li *et al.*, 2025).

Microbial biosensors and sustainability

Microbial biosensors may help make environmental monitoring faster, more accessible and more biologically meaningful. Some systems use small sample volumes and relatively simple equipment and portable designs may be useful where access to advanced laboratories is limited. Their cost and ease of use vary with the sensor design, target and measurement system; they should not automatically be assumed to be cheaper than all conventional methods. Combining microbial biosensors with microfluidics, smartphones, wireless communication and data-analysis tools may create opportunities for near real time monitoring. For example, a portable device could record a sensor response and transmit the data for interpretation. In agriculture, such systems could eventually support the screening of soil contamination or the early detection of toxic stress in water. These are developing opportunities rather than routine capabilities of every microbial biosensor.

Advantages and limitations

Microbial biosensors can be sensitive, relatively rapid and adaptable to different targets. Whole cell systems may provide biologically relevant information about the fraction of a contaminant that affects living cells. Nevertheless, their response can be influenced by temperature, pH, oxygen availability, nutrient status and the complexity of soil or water samples. Some systems respond to general toxicity rather than identifying a particular chemical. Genetically engineered microorganisms also require appropriate biosafety measures and containment. For these reasons, microbial biosensors are best viewed as complementary tools that can support environmental screening and monitoring, while conventional analytical methods remain important for confirming and identifying contaminants.

Future prospects

Future progress will depend on advances in synthetic biology, materials science, electronics and data analysis. Engineered sensing pathways may improve target recognition, while suitable materials and electrode interfaces may strengthen signal detection. Portable electronics could make the results easier to record and interpret. These advances must be accompanied by testing for reliability, stability, selectivity and safety. Field deployable microbial bioelectronics sensors are an active area of research. Laboratory studies show promise for rapid environmental sensing, but sensitivity, specificity, operational lifetime and robustness under real world conditions still need improvement before widespread use.

Conclusion

Environmental pollution requires monitoring approaches that are accurate, timely and informative about biological effects. Microbial biosensors use the responses of living microorganisms to detect or assess nutrients and contaminants in soil, water and other environments. Their key strength is that they can connect chemical exposure with a biological response, including information about bioavailability or toxicity. They are not replacements for all conventional analytical methods, but they may complement them by supporting rapid screening and, in some cases, field based monitoring. Continued advances in biosensing, electronics and data analysis could expand their role in sustainable environmental management.

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