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Original article

Toward safer environment: Emerging biosensor solutions for pesticides detection

Ankur Tomar[1], Sapna Katna[1], Tanuja Banshtu[1], Taniya Katoch[1] and Manisha Sharma[1]*

[1]Department of Entomology, Dr YS Parmar University of Horticulture and Forestry, Nauni, Solan, H.P. 173230

**Corresponding author: maneeshasharma567@gmail.com*

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ABSTRACT

The escalating use of toxic chemicals and pesticides in agriculture and industry has heightened the demand for sensitive, rapid, and cost-effective detection methods. Traditional analytical techniques, although accurate, are limited by high costs, complex procedures, and the need for trained personnel. Biosensors have emerged as promising alternatives, offering portability, high specificity, and real-time monitoring capabilities. Various biosensors including electrochemical, optical and mechanical have been successfully utilized for the detection of pesticides from food and water samples. These biosensors can be utilized for detection of toxic chemicals in agriculture, environment monitoring, and food safety as well as in medical science. However, some of the challenges related to utility of these biosensors include stability, calibration, reproducibility and multiple residue detection which can be overcome by modification of these biosensors by fitting multiple sensors, integration of artificial intelligence and wearable biosensors for real time analysis.

INTRODUCTION

Widespread industrialization and agricultural intensification have significantly increased the prevalence of environmental pollutants, particularly pesticides and industrial chemicals. These substances, when accumulated in the ecosystem, pose severe health and ecological threats. Detecting them accurately and efficiently is essential to ensure compliance with environmental safety regulations and to mitigate public health risks (Turner, 2013). Conventional detection techniques, including gas chromatography (GC), high-performance liquid chromatography (HPLC), and mass spectrometry (MS), are known for their precision. However, they are hindered by high cost, complex sample preparation, and lack of portability (Dincer et al. 2019). These limitations have driven the need for alternative approaches that can provide on-site, real-time monitoring without compromising accuracy. Biosensors have gained prominence due to their specificity, affordability, and rapid response times. These devices convert biological interactions into measurable signals using various transduction mechanisms. With recent advances in biotechnology, nanotechnology, and material sciences, biosensors have become increasingly sophisticated and versatile (Lim et al. 2021). This article presents an integrated review of biosensor technologies for detecting chemicals and pesticides where, we explore sensor mechanisms, innovations, applications, and existing limitations. We also identify future research directions aimed at improving sensor sensitivity, selectivity, and commercial viability.

1. Overview of Biosensor Technology

A biosensor is composed of three main components: a bio-recognition element, a transducer, and a signal processor. The bio-recognition element—such as an enzyme or antibody—specifically interacts with the target analyte. The transducer then converts this interaction into a quantifiable signal, often electrical, optical, or mechanical in nature (Pundir et al. 2020). The growing interest in biosensor stems from their ability to provide field-deployable solutions with minimal sample preparation. Their design flexibility allows adaptation across a wide range of applications, from environmental monitoring to food safety and healthcare diagnostics (Yáñez-Sedeño et al. 2017).

2. Classification of Biosensors by Transduction Mechanism

Biosensors for chemical and pesticide detection are classified into three main types based on their detection mechanisms: electrochemical, optical, and mechanical methods.

Electrochemical biosensors are widely used due to their simplicity, sensitivity, and low cost. These include screen-printed electrodes, which are commonly used for portable and on-site testing, Field Effect Transistor (FET)-based sensors, which offer high sensitivity for detecting low concentrations of analytes, and capacitive-based methods that measure changes in capacitance upon analyte interaction (Table 1) (Kaur and Prabhakar 2017). On the other hand, optical detection methods offer high specificity and are often used for more detailed analysis. These methods include optical-MEMS (Micro-Electro-Mechanical Systems) sensors, colorimetric assays that produce a colour change upon interaction with the target analyte, and advanced techniques like Surface-enhanced Raman scattering (SERS) and Surface Plasmon Resonance (SPR), which detect molecular interactions by analyzing light properties (Table 1). Additionally, chemiluminescent and fluorescent methods are employed for real-time monitoring of chemical presence (Chawla et al. 2018). Mechanical detection methods, which rely on physical changes in response to analyte binding, include mass-sensitive sensors like microcantilever deflection, bulk acoustic wave devices such as Film Bulk Acoustic Resonators (FBAR) and Quartz Crystal Microbalance (QCM) sensors (Table 1). Each method has unique advantages and limitations, which influence their application in various fields, from environmental monitoring to food safety and medical diagnostics (Verma and Bhardwaj 2015).

Biosensors designed for pesticide detection utilize a variety of biorecognition materials, such as aptamers, antibodies, and enzymes, to interact specifically with the target pesticide residues. These sensors function based on affinity biosensing, which involves the recognition of an analyte (in this case, pesticide residue) by a biorecognition element and the subsequent conversion of this interaction into a measurable signal. Affinity biosensors are categorized into two types: labelled and label-free biosensors (Capoferri et al. 2018). Labelled biosensors use markers to confirm the binding interaction between the target pesticide and the probe. Common labels include fluorescence markers (quantum dots), radioactive species, magnetic beads, and active enzymes (Narenderan et al. 2020). Labelled biosensors offer fast, accurate, and straightforward detection but come with significant drawbacks. The labelling process can interfere with the interaction between the target analyte and the biorecognition element, which can impact the accuracy of the measurements. Additionally, the process of labelling requires additional materials and instruments, which increases both the cost and complexity of the system. Furthermore, the labelling process is time-consuming and typically requires sophisticated equipment to measure the fluorescence signals, making it unsuitable for field-deployable applications and limiting miniaturization (Verma and Bhardwaj 2015).

In contrast, label-free biosensors offer a simpler alternative by directly detecting the analyte without the need for any labels or markers. This method is advantageous because it avoids the issues associated with the labelling process and can provide more rapid and direct measurements. However, the label-free method requires a highly sensitive transducer to detect any changes during the interaction between the biorecognition element and the pesticide residue. The binding interaction between the probe and target must be highly specific to ensure accurate detection (Sadik et al. 2009).

Table. 1 Examples of different biosensors used in pesticide detection

Type	Principle of detection	Target pesticide and sample	Bio-recognition	Limit of detection
Electrochemicals biosensors	Resistance change	Atrazine from grapes	Antibody	8.3 μg L^{-1}
	Current change	Imidacloprid from tomato and tap water	Antibody	22 pM
	Current change	Paraoxon from spinach	Enzyme	0.03 μg L^{-1}
	Resistance change	Malathion and cadusafos from Tap water	N/A	0.1 nM L^{-1}
	Impedance change	Acetamiprid from Tomato	Aptamer	1 nM
	Impedance change	Carbendazim from Tap water	Aptamer	0.9 ng ml^{-1}
Optical	SPR– Wavelength	Dimethoate and	Molecular	8.37 & 7.11

biosensors	change	Carbofuran from Water	imprinted	ng L^{-1}, respectively
	Fluoroscence–Intensity change	Malathion from water	Aptamer	4 pM
	SERS– Intensity change	Malathion from tap water	Aptamer	N/A
	Colorimetric-Colour change	Malathion	Aptamer	0.06 pM
Mechanical based biosensors	FBAR- shear mode with ZnO film	Chlorpyrifos	Frequency 1.47 GHz	4.1×10^{-11} M
	Electrostatic actuation – capacitive sensing MEMS	Mercury acetate	Frequency 32 – 39 MHz	N/A

Modified after Hashwan et al. (2020)

Enzymatic biosensors have been among the most widely used tools in pesticide detection. These sensors utilize enzymes that interact specifically with pesticide residues, offering highly sensitive detection, with the ability to detect pesticide levels as low as 10^{-10} M (Songa and Okonkwo 2016). However, they also have several limitations. The short lifetime of enzymes, along with potential interference from other substances such as heavy metals and different types of pesticides, can reduce the specificity and reliability of these biosensors. Additionally, enzymatic biosensors require longer incubation times, which can be a disadvantage in scenarios requiring rapid results. Another widely used technique is the enzyme-linked immunosorbent assay (ELISA), which is known for its high sensitivity and specificity. However, it requires the labelling of molecules, which can affect the detection of small pesticide molecules due to the potential alteration of their chemical properties during the labelling process (Bala et al. 2018). Furthermore, antibody-based immunoassays, although effective for large molecules, are challenging when applied to small pesticide residues, as the preparation of antibodies for such small molecules is complex and often inefficient.

To overcome the drawbacks of enzyme and antibody-based biosensors, aptamers have emerged as promising alternative biorecognition materials. Aptamers are small, synthetic oligonucleotides that can bind to specific target molecules, including pesticides, with high specificity (Fu et al. 2019). They offer several advantages over traditional enzymes and antibodies, including simpler preparation, higher stability, and the ability to be tailored to bind a wide variety of targets. Additionally, aptamers can be used in label-free biosensors, which are more suitable for field applications and on-site pesticide detection. The development of aptamer-based biosensors represents a significant advancement in the field, offering more efficient and reliable solutions for pesticide residue detection.

5. Applications of Biosensors

5.1 Agriculture

In agriculture, biosensors are used for monitoring pesticide residues in soil and crops. For instance, amperometric biosensors have been employed to detect atrazine in agricultural runoff (Pundir et al. 2020).

5.2 Environmental Monitoring

Biosensors play a crucial role in monitoring water quality by detecting pollutants such as heavy metals and pesticides. AChE-based sensors have been used for field testing of water bodies near industrial zones (Yáñez-Sedeño et al. 2017).

5.3 Food Safety

Biosensors are being used for detecting chemical contaminants in food products, ensuring compliance with regulatory standards and consumer safety (Dincer et al. 2019).

5.4 Medical and Toxicological Applications

Biosensors can detect biomarkers related to chemical exposure in human samples like sweat, saliva, or blood, providing rapid assessment in occupational health scenarios (Turner, 2013).

6. Current Challenges

While biosensors have shown promise, several barriers hinder their widespread use:

- **Selectivity and Cross-Reactivity**: Environmental samples may contain interfering substances.
- **Stability**: Biological recognition elements often have limited shelf life.
- **Calibration and Reproducibility**: Standardization is needed for consistent results (
- **Regulatory Approval**: Biosensors must undergo rigorous validation for public health applications.
- **Simultaneous multiple analyte detection**: Sensors are specific for certain group of pesticides and can't detect multiple pesticides.

7. Future Trends

- **Synthetic Biology** for producing robust biorecognition molecules.
- **Multiplexed Sensors** capable of detecting multiple analytes simultaneously.
- **AI-Integrated Systems** for advanced signal processing and decision-making.

- **Wearable Biosensors** for real-time exposure monitoring in industrial and agricultural workers.

CONCLUSION

Biosensors represent a significant leap forward in the detection of toxic chemicals and pesticides. Compared to conventional laboratory-based methods, biosensors offer rapid detection, cost-effectiveness, and portability, making them ideal for applications in environmental monitoring, food safety, and agriculture. Recent advances in nanomaterials, synthetic biology, and electronics have dramatically enhanced biosensor capabilities. As shown in the IEEE study by Pundir et al. (2020), these innovations have enabled the development of sensitive, selective, and field-deployable devices. However, challenges such as sensor longevity, reproducibility, regulatory acceptance, and simultaneous multiple analyte detection remain critical hurdles. Addressing these limitations will require multidisciplinary collaboration and innovation. The future of biosensors lies in integrating them with IoT frameworks, AI-driven data analytics, and robust biorecognition platforms. Such convergence will enable real-time, on-site analysis that informs decision-making processes, improves regulatory compliance, and safeguards public health. This article consolidates the current landscape of biosensor technologies for chemical and pesticide detection, highlights their transformative potential, and outlines the roadmap for future advancements. With the right investments and research initiatives, biosensors are poised to play a pivotal role in the next generation of environmental and health monitoring systems.

REFERENCES

Bala, R., Swami, A., Tabujew, I., Peneva, K., Wangoo, N. and Sharma, R.K. (2018). Ultra-sensitive detection of malathion using quantum dots-polymer based fluorescence aptasensor. *Biosensors and Bioelectronics*, *104*, pp.45-49. https://doi.org/10.1016/j.bios.2017.12.034

Capoferri, D., Della Pelle, F., Del Carlo, M. and Compagnone, D. (2018). Affinity sensing strategies for the detection of pesticides in food. *Foods*, *7*(9), p.148. https://doi.org/10.3390/foods7090148

Chawla, P., Kaushik, R., Swaraj, V.S. and Kumar, N. (2018). Organophosphorus pesticides residues in food and their colorimetric detection. *Environmental nanotechnology, monitoring & management*, *10*, pp.292-307. https://doi.org/10.1016/j.enmm.2018.07.013

Dincer, C., Bruch, R., Kling, A., Dittrich, P. S., & Urban, G. A. (2019). Multiplexed point-of-care testing – xPOCT. *Trends in Biotechnology*, 37(7), 728–742.

Fu, J., An, X., Yao, Y., Guo, Y. and Sun, X. (2019). Electrochemical aptasensor based on one step co-electrodeposition of aptamer and GO-CuNPs nanocomposite for organophosphorus pesticide detection. *Sensors and Actuators B: Chemical*, *287*, pp.503-509. https://doi.org/10.1016/j.snb.2019.02.057

Hashwan, S., S., B., Khir M., H., B., D., Douri Y., A., & Ahmed A., Y. (2020) "Recent Progress in the Development of Biosensors for Chemicals andPesticides Detection," in *IEEE Access*, *8*, pp. 82514-82527.

Kaur, N. and Prabhakar, N. (2017). Current scenario in organophosphates detection using electrochemical biosensors. *TrAC Trends in Analytical Chemistry*, *92*, pp.62-85. https://doi.org/10.1016/j.trac.2017.04.012

Lim, S. A., Ahmed, M. U., & Park, S. Y. (2021). Recent advances in biosensor technologies for environmental monitoring. *Sensors and Actuators B: Chemical*, 343, 130114.

Narenderan, S.T., Meyyanathan, S.N. and Babu, B.J.F.R.I. (2020). Review of pesticide residue analysis in fruits and vegetables. Pre-treatment, extraction and detection techniques. *Food Research International*, *133*, p.109141. https://doi.org/10.1016/j.foodres.2020.109141

Pundir, C. S., Chauhan, N., Narang, J., & Hashmi, A. A. (2020). Recent Progress in the Development of Biosensors for Chemicals and Pesticides Detection. *IEEE Access, 8*, 55299–55314. https://doi.org/10.1109/ACCESS.2020.2981705

Sadik, O.A., Aluoch, A.O. and Zhou, A. (2009). Status of biomolecular recognition using electrochemical techniques. *Biosensors and Bioelectronics*, *24*(9), pp.2749-2765. https://doi.org/10.1016/j.bios.2008.10.003

Songa, E.A. and Okonkwo, J.O. (2016). Recent approaches to improving selectivity and sensitivity of enzyme-based biosensors for organophosphorus pesticides: A review. *Talanta*, *155*, pp.289-304. https://doi.org/10.1016/j.talanta.2016.04.046

Turner, A. P. F. (2013). Biosensors: sense and sensibility. *Chemical Society Reviews*, 42(8), 3184–3196.

Verma, N. and Bhardwaj, A. (2015). Biosensor technology for pesticides—a review. *Applied biochemistry and biotechnology*, *175*, pp.3093-3119. https://doi.org/10.1007/s12010-015-1489-2

Yáñez-Sedeño, P., Campuzano, S., & Pingarrón, J. M. (2017). Electrochemical biosensors for pesticide detection. *TrAC Trends in Analytical Chemistry*, 94, 39–53.