International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Nanosensor and Nanobiosensor in Agriculture and Environmental Monitoring: A Review

Vasandhara Devi R[1], Subashini C[2], Chandran Masi[3]

[1,2]Department of Biotechnology, Dhanalakshmi Srinivasan Engineering College, Perambalur, Tamil Nadu, India.

[3]Department of Food Technology, Dhanalakshmi Srinivasan Engineering College, Perambalur, Tamil Nadu, India.

Abstract

Nanobiosensors are an advanced type of analytical device that combine nanomaterials with biological recognition components, allowing for ultra-sensitive and selective detection of various chemical and biological targets. In the field of agriculture, these systems enable quick, real-time monitoring of soil nutrients, early detection of plant diseases, assessment of pesticide levels, and evaluation of crop health, thereby enhancing precision farming techniques. The use of nanoscale materials such as gold nanoparticles, carbon nanotubes, graphene, magnetic nanoparticles and quantum dots significantly boosts sensitivity, response times, and stability. These improvements facilitate more precise diagnostics in the field and decrease reliance on traditional laboratory methods. In environmental monitoring, nanobiosensors have shown remarkable effectiveness in identifying heavy metals, microbial pollutants, organic contaminants, and new toxic substances in soil, water, and air. Their compact design, portability, and ability to integrate with wireless and IoT-enabled systems allow for ongoing, autonomous environmental monitoring. Recent developments also feature flexible, wearable, and paper-based sensors that offer economical and eco-friendly monitoring solutions suitable for widespread implementation. This review highlights the vital role of nano biosensors in facilitating precision agriculture and protecting the environment while pinpointing crucial areas for future development.

Keywords: Nanobiosensors, Precision agriculture, Environment monitoring, Nanomaterials, Heavy metal detection, Plant disease detection.

1. Introduction

A relatively new and quickly expanding trend in practically every scientific field is nanotechnology. The idea behind nanotechnology is to work atom by atom to create structures with novel molecular organization. By doing so, it is possible to take advantage of these characteristics and create novel devices (Sharon et al., 2010).

Sensors are sensors with at least one sensing component that is smaller than 100 nm. The unique electrochemical properties of nanomaterials can be utilized for detection in the development of such nano sensors.

The development of diagnostic tools and techniques, such as nano-biosensors, is a major factor in the agricultural revolution. These sensors are accurate, efficient, and cost-effective when it comes to managing various food, agricultural, and environmental issues. Sensor applications in agriculture include the detection of heavy metal ions, pollutants, microbial load, and pathogens in addition to rapid temperature, traceability, and humidity monitoring (Jhonson et al., 2021).

Nanosensors can be applied in a variety of fields, including environmental, agricultural, medical and industrial (Joseph et al., 2006).Agriculture uses a variety of strategies based on more ecologically friendly and energy-efficient cross-cutting technologies, such as: i) nano formulation delivery systems to enhance the wettability and dispersion of nutrients and yield mapping, and positioning systems for crop growth and disease control (Fraceto et al., 2016).A various of nanomaterials, including metals, carbon nanotubes (CNTs), magnetic nanoparticles, nanowires, nano-probes, and quantum dots (QDs), are used to create nano biosensors, which are made of nanocomposites of organic, inorganic, or combined materials (Periakaruppan et al., 2013).

Nanoparticle-integrated biosensors, or nano sensors, are recent developments in the field of nanotechnology. They are essential to the agri-food industry because they are compact, portable, effective, sensitive, and specific. Nanoparticle-based nano biosensors can be used by researchers in clinical diagnostics and research facilities for smaller delivery systems, plant protection, improved oil health promotion, longer fruit shelf life, and sustainable agriculture (Dar et al., 2020).

Farmers in the agricultural sector can monitor and manage soil conditions on-site with the help of these small, portable, and compact devices. Nano biosensors have been used to analyse soil fertility, pH, moisture content, mineral concentrations, pest detection, and mineral deficiencies prior to disease onset. A biological component is incorporated into nano biosensors to help them sense and measure desired aspects. Peptides, enzymes, antibodies, cells, tissues, and nucleotide structures are examples of these. These are connected to a detection technique, frequently a transducer, to produce an electronic signal. Additional detection techniques include fluorescent-based reactions that resemble miniature bedside testing strips or visible colour changes. The potential for higher sensitivity (identifying individual virus particles) and the high surface area of small-scale reactions, which reduce reaction times and sample quantities and improve result efficiency, are two advantages of nano biosensors over conventional biosensors.

High levels of research and optimization have been applied to smartphone integrated systems for such applications, eliminating the need to buy particular electronic devices. Nano biosensors are currently being developed for a variety of purposes, such as the detection of corn mycotoxins, subclinical ketosis, and different types of influenza. There is currently nano technology that provides a real-time, field-based diagnosis of pathogenic contamination. These tools show promise for food analysis because they can meet certain needs that traditional analytical techniques cannot (Viswanathan & Radecki 2008).This study aims to review the use of biosensors and nano biosensors in the environmental and agricultural sectors.

2. Nanosensors and Nanobiosensors

A sensor is a device that can identify and quantify the presence of an analyte in a sample. A transducer, a readout system, and a detection system known as a receptor (receptor) make up the sensor.

A biological component, the acceptor in biosensors is fixed to the converter in various ways (Huang et al., 2021). Biosensors are analytical tools that combine biological materials, like cells, antibodies, enzymes, etc. a biologically derived surface connected to a transducing system, which may be magnetic, optical, electrochemical, or piezoelectric is shown in fig.1 (Schaertel and Firstenberg-Eden 1988).

In biochemical, clinical, food, and environmental analyses, biosensors are effective instruments for examining biomolecular interactions (Hock et al., 2002). Normal micro and macro-sized materials make up the receptor and transducer materials in a biosensor, but in a nano biosensor, either the receptor or the transducer, or both, are composed of nano material. For a variety of field applications, carbon-based, metal-based, polymer-based, and nanocomposite materials are primarily utilized (Khan et al., 2019). Recent developments in nanotechnology make it possible to create nanomaterials with remarkable optical and electrical characteristics for use in electronics and sensing applications (Saini et al., 2017).

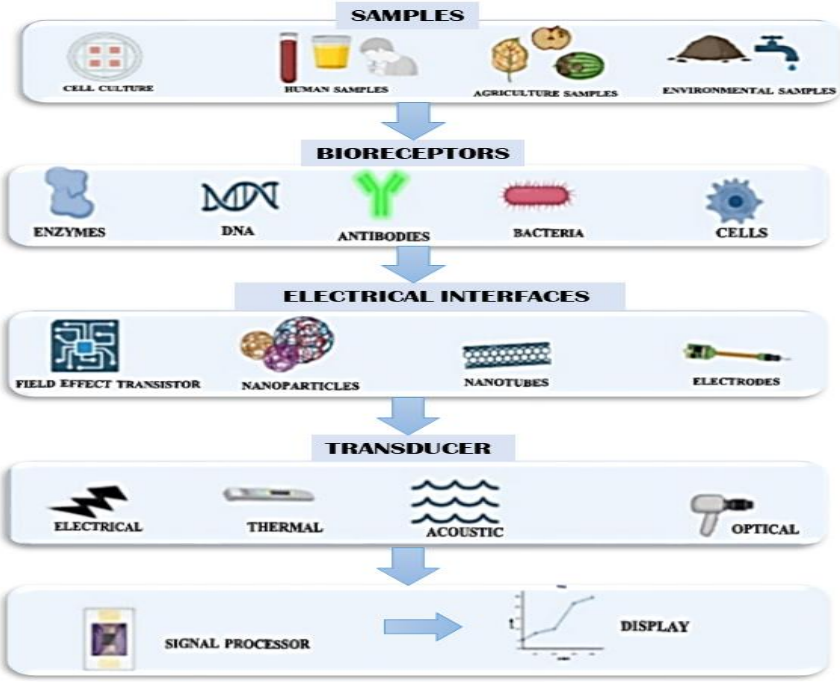

Figure 1: Basic structure of nanobiosensor

3. Types of Nanobiosensor

Nano-biosensors are generally categorized according to the nature of the identified compound, the transduction system, the identification technique used to identify the interactions, and the interaction between the probe and the analyte element. Nano-biosensors are commonly categorized in agricultural and environmental applications is given in fig. 2. Based on the biological element or receptors, biosensors are generally divided into two categories: enzyme-based, antibody-based, and aptamer-based.

Enzyme-based biosensors have demonstrated uses in the environmental, agricultural, pharmaceutical, and food quality and safety sectors. They function by utilizing the redox reactions of different enzymes (Ghorbanpour et al., 2020).

Aptamer-based biosensors are made up of DNA/RNA oligonucleotides that interact with their target ligands. These aptamers are able to identify and attach to small molecules of interest, altering their structures. Applications for aptamer-based biosensors in environmental monitoring, particularly in water contamination, include the detection of bacterial cells, bacterial toxins, viruses, mycotoxins, or heavy metals. Pesticides, pharmaceuticals, industrial byproducts, antibiotics, and aquatic toxins are also targets (McConnell 2020; Chiu and Huang 2009). Antibody-based biosensors make use of antibodies' ability to recognize specific amino acid segments. Environmental and clinical applications have made use of these sensors (Wujcik et al., 2014).

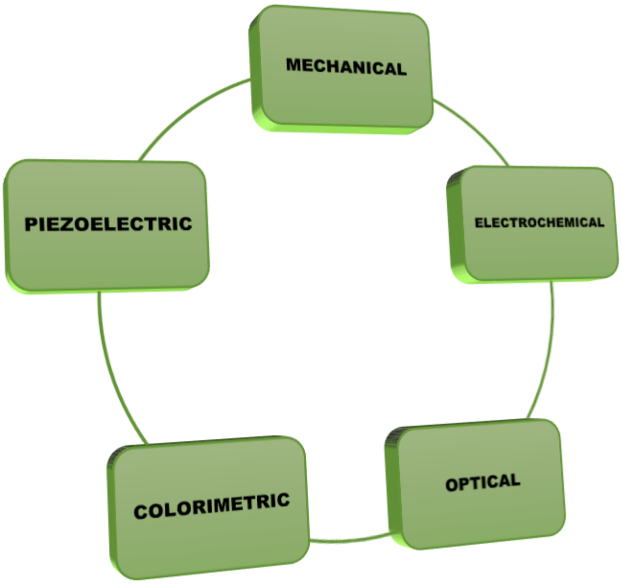

Figure 2: Types of Nanobiosensors based on agriculture and environmental applications.

3.1 Mechanical Nano biosensor

Nanoparticle-based mechanical detection systems measure changes in mechanical forces at the molecular level and enable ultrasensitive detection. Mechanical nano-biosensors quantify the nanoscale forces produced by changes in mechanical properties or biomolecular interactions. That is surface stresses, expansion, deformation, motion), as well as physical (forces, weights) (Purohit et al., 2020). Compared to other biosensors, mechanical biosensors have certain advantages. Initially, biosensors based on bio affinity that can identify even the tiniest quantities of analyte (e.g.) can be created utilizing the outstanding mass resolution of these devices. Nanoelectromechanical systems (NEMS) have achieved a mass resolution at the zeptogram scale (Braun et al., 2009).

Second, these devices can be used to quantify forces at the cellular level because they experience a measurable displacement in response to an applied force that can be converted to an electric signal (Polacheck et al., 2016).

Third, they have a very fast sensing time, required to study biological events. Fourth, the feasibility of detecting an analyte in both liquids, and gaseous phases. Fifth, no need for labelling in these devices, which is an essential requirement in optical sensing (Rodahl et al., 1995). In agriculture, mechanical nano biosensors are instruments that use nanoscale mechanical principles to identify and track soil conditions, plant health, and the presence of pollutants.

3.2 Electrochemical Nano biosensor

Electrochemical sensors are applicable to a wide range of analytes. Electrical recognition is a rapidly growing field that requires little effort in manufacturing processes. The remarkable qualities of electrochemical detection, such as its sensitivity, low cost, compatibility with contemporary miniaturized/lab-on-a-chip strategies, minimal power requirements, and lack of pre-sample processing (no effect from turbidity and colour of sample), are what make it so popular (Zhu et al., 2015).

The standard principle of electrochemical nano sensors is a chemical reaction in which electron release, accept or consume ions. This chemical reaction takes place between a restrained ligand and analyte of interest that measurably affect the transduced signal, such as an electrical current or potential (Cheng et al., 2006).

Electro chemical nano sensors work on the basis of a chemical reaction in which electrons release, accept, or consume ions. This chemical reaction occurs between an analyte of interest, such as an electrical current or potential, and a restrained ligand that has a measurable impact on the transduced signal (Hameed et al., 2017). These electrochemical sensors have been employed to identify both biological and chemical substances, offering a diverse array of applications in the fields of environmental science and biomedicine (Bakirhan et al., 2020). Various kinds of electrochemical sensors exist and can be categorized into A ampero metric, photo-electrochemical, impedance, and electrochemical luminescence (Hammond et al., 2016).

3.3 optical Nano biosensor

Detection of optical signals using nano sensors delivers enhanced sensitivity due to the unique interactions between the active sites of nanomaterials and light signals. Nonetheless, the level of sensitivity is heavily influenced by the specific detection mode of the optical phenomena (Wang et al., 2012).

Optical sensors are utilized for various types of spectrographic assessments, including absorption, visible light, fluorescence, Raman spectroscopy, surface-enhanced Raman scattering (SERS), refraction, and qualitative analysis through dispersion (Lee et al., 2011). These sensors enable various applications such as monitoring soil health, managing nutrients, detecting diseases, and optimizing water quality. They employ nanotechnology to improve decision-making in agriculture, decrease the use of agrochemicals, and boost crop yields while lessening environmental effects. Optical nanobiosensors can revolutionize agricultural systems, offering economic benefits through reduced input costs and increased yield quality while contributing to environmental sustainability and long-term food security (Kumar et al., 2025).

3.4 Colorimetric Nano biosensor

Colorimetric biosensors can identify interactions with certain analytes by observing changes in colour, enabling both straightforward and immediate diagnostic techniques (Zhu et al., 2020; Liu et al., 2020). Colorimetric sensors have been designed exploiting the pronounced localized SPR of gold colloids, and colour changes depending on the interparticle distance of nanoparticles. Colorimetric biosensors are capable of identifying reactions with particular analytes by means of colour alterations, enabling both straightforward and immediate diagnostic techniques (Zhu 2020; Liu 2020).

Colorimetric biosensors are gaining significant interest because of their distinctive characteristics, including straightforward visual detection, excellent sensitivity, and reduced reliance on devices. In particular, in clinical and field applications, there is a critical need for a sensing system that is immediate, highly sensitive, and cost-effective for diagnosis (Yokoori 2025; Zhang 2020). Various types of nanomaterials are utilized in researching biosensors, particularly in the realm of colorimetric biosensors (Nguyen et al., 2020). Colorimetric biosensors have found extensive use in the testing of mycotoxins (Zhu et al., 2020).

3.5 Piezoelectric Nano biosensor

The piezoelectric sensor operates by detecting variations in mechanical stress caused by the binding of biomolecules to the surface of the piezoelectric crystal, along with the voltage generated when the material experiences mechanical stress (Pohanka et al., 2018). A piezoelectric material or crystal, like lead zirconate titanate or barium titanate, serves as the central sensing component in a piezoelectric nano-biosensor (Selvarajan et al., 2017). Research has been conducted on these sensors for their potential use in different environmental and healthcare settings, including the detection of foodborne pathogens and toxins (Malekzad et al., 2017).

4. **Nanomaterials Used in Nano Biosensors**

Nanomaterials have been utilized to create nano biosensors or nanoparticle-based biosensors by integrating nanoparticles into the sensor design. The small size (1–100 nm) and increased surface area of nanomaterials enhance the efficiency of biosensors (Antonacci et al., 2018). Various types of nanomaterials have been utilized in the creation of biosensors, including metallic nanoparticles, metal oxides, quantum dots, and dendrimers (Forough 2021; Xiang 2015).

Biosensors that use nanomaterials exhibit excellent sensitivity, quick detection rates, and rapid response times. Optical biosensors, including fluorescence sensors and surface plasmon resonance sensors, as well as electrochemical biosensors such as amperometric, potentiometric, conductometric, and impedimetric sensors, along with mass-based piezoelectric biosensors, can be enhanced by incorporating nanomaterials to improve their detection capabilities (Santos 2018; Mohammadi 2020).

Nanomaterials find widespread applications in agriculture owing to their size and enhanced characteristics. Their unique physical, chemical, and biological properties cause them to function quite differently than bulk materials (Garg et al., 2022). Nanomaterials serve various purposes, including identifying pollutants in soil, cleaning water, combating plant diseases, and enhancing the capacity of plants to gradually uptake nutrients (Yata et al., 2018).

The eco-friendly synthesized nanoparticles, including silver (Ag), gold (Au), zinc oxide (Zn O), and titanium dioxide ($TiO2$), are widely employed in plant protection for managing diseases and enabling early detection of infections (Cardoso et al., 2022). Nano fertilizers incorporating metal nanoparticles have been utilized to sustain crop nutrition (Kubavat et al., 2020). (Table 1) illustrates the various nanoparticle-based biosensors and the detection limits employed in recent years.

Metallic nanoparticles, including silver (Ag), gold (Au), zinc oxide (ZnO), and iron oxide ($Fe2O3$), are some of the most widely researched nanomaterials due to their diverse applications in agriculture. Silver nanoparticles (Ag NPs) are very efficient in managing plant pathogens, while zinc oxide nanoparticles (ZnO NPs) improve the accessibility of micronutrients, thus promoting plant growth and development (Trzcińska-Wencel et al., 2018). Carbon-based nanomaterials like carbon nanotubes (CNTs), graphene oxide, and fullerenes are becoming increasingly important in agriculture due to their structural integrity and capacity to affect plant physiological functions (Pandey et al., 2019). Graphene oxide has shown the capacity to manage oxidative stress in plants and enhance the effective distribution of agrochemicals. Moreover, the distinctive electrical and mechanical characteristics of carbon-based nanomaterials render them exceptionally appropriate for biosensing applications, allowing for the real-time observation of plant well-being and environmental factors (Gao et al., 2020). Chitosan-based nanoparticles are eco-friendly and have antimicrobial characteristics, making them suitable for sustainable pest control. These polymer systems not only minimize the environmental impact of farming practices but also help to sustain or improve crop yields (Kumaraswamy et al., 2018).

Table 1: Nanomaterials used in Nanobiosensor

S.no	Nanomaterials	Sensing types	Analyte	Linear Range	Detection limit	Reference
1.	Cu O/GO	Electrochemical	Glucose	0.0028–2.03 mM	0.1nM to 5µM	Song et al., (2013).
2.	Cu O Gr/CPE	DPV	Caffeine	0.025–0.3µM	0.010µM	Khoshhesab et al., (2015).
3.	Fe2O3 NPs	Electrochemical	Uric Acid	10–100µM	2.5nM	Cai et al., (2019).
4.	Poly pyrrole - chitosan-Iron oxide	Electrochemical	Glucose	1–16 mM	234µM	Mokaram et al., (2016).
5.	Au NPs	Electrochemical	E. coli	10_106 CFU mL−1	15 CFU mL −1	Vu et al., (2020).

6.	Zn ONFs	Optical	Amyloid	2–20 µ L	2.76µg	Akthar et al., (2017).
7.	DNA based biosensor	Electrochemical	Detection of Phytophthorapulmivora causing black pod rot in cacao pod	--	0.30 ng DNA/µ L	James et al., (2019).
8.	Multiwalled carbon nanotube	SPR	Detection of Cymbidium Mosaic virus	--	40 p M	Antonacci et al., (2018).
9.	SWCNTs	Piezo electric and optic based	Detection of small toxin molecules in food	--	n M -f M level	Bahadır and Sezgintürk (2017).
10.	Aptamers	Aptameric biosensors	Detection of pathogens	--	5.0nM	Sharma et al., (2020).
11.	Sol–gel derived Zn O nanoparticles	β-galactosidase based	Detection of E. coli	--	101 CFU/mL	Meraat et al., (2020).
12.	Enzyme	Amperometric	Detection of Malathion	--	0.001µg/L	Zhang et al., (2019).
13.	Enzyme	Differential pulse voltammetry	Detection of paraoxon	--	1.1ng/mL, 12min	Mohammed et al., (2018).

5. Application of Nano Biosensor in Agriculture and Environmental Monitoring

In order to uphold sustainable agriculture, the adoption of advanced technology is essential, including the use of nano biosensors. Nano biosensors provide an affordable detection solution with enhanced sensitivity for the agri-food sector (Kumar 2021; Sharma 2021).

Overall, the application of nano biosensors has been aiding the advancement of "smart agriculture" and/or "precision farming," owing to their capacity to sense, analyse, and identify changes (Manjunatha et al., 2016). Intelligent plant systems facilitate quick evaluation and effective administration of expensive agrochemicals, environmental stress factors, and phytopathogens that contribute to significant crop loss. Continuous plant monitoring can be a labour -intensive task that can be accurately performed with the aid of smart nano biological sensors (Mittal et al., 2020). Improvement in sensing technology can be obtained by linking the nano biosensor with a global positioning system, which can significantly assist farmers in isolated regions to oversee the use of fertilizers, pesticides, insecticides, water levels, and manage both physical and chemical stresses, as well as detect pathogens to avert the emergence of various diseases in crops directly in their fields (Shang et al., 2019).

5.1 Detection of pest/pathogens in plant

In the early years, identifying particular pathogens primarily relied on their visualization, often requiring multiple days (Khiyami et al., 2014). Timely identification of pathogens through innovative biosensing methods contributes to effective disease management, resulting in reduced productivity losses. Accurately pinpointing pathogens can aid in formulating treatment plans to tackle diseases (Ali et al., 2021).

Plant pathogens can also be found, including Acidovorax avenae, Pseudomonas syringae, Ralstonia solanacearum, Pantoea stewartii, Botrytis cinerea, Pseudocercospora fijiensis, Leptosphaeria maculans, and others (Dyussembayev et al., 2021). The creation of straightforward and quick sensing tools or platforms has been crucial in the field of plant disease management research.

In contemporary agriculture, biosensors that utilize nanomaterials are employed as a rapid detection method. Various biosensing approaches have been developed by researchers, including electrochemical sensing, immune sensing, and apta sensing, among others (Cebula et al., 2019). A label-free electrochemical biosensor using impedance detection has been developed to identify Pseudomonas syringae pv. lachrymans (Psl), achieving a limit of detection of 337 CFU/m L. Another electrochemical sensor was developed to identify Pseudomonas syringae DC3000 (Psy) with a limit of detection of 214 p M (Lau et al., 2017). Created an alternative method for colorimetric detection of Pseudomonas syringae utilizing thiol-linked DNA-Gold nanoparticle probes.

The detection mechanism is based on a colour shift (from red to purple) during the process, which verifies a positive outcome. The soil bacterium Ralstonia solanacearum, responsible for potato wilt disease, was identified, and a comparable colorimetric detection method was also created. The pathogen can be directly identified from the soil sample (Khaledian et al., 2017). Nano biosensors that utilize the fluorescence resonance energy transfer phenomenon of quantum dots have been employed for the detection of Phytoplasma aurantifolia, which causes witches' broom disease in lemon trees. An immunosensor method has been applied to enhance sensitivity to a full 100% (Duhan et al., 2017).

Nano chips designed for microarrays incorporate fluorescent capture probes to identify single nucleotide variations in bacteria and viruses (Kaushal and Wani 2017). Pathogens are recognized, and the data obtained are utilized for enhancing crop varieties, as demonstrated in Fig. 3.

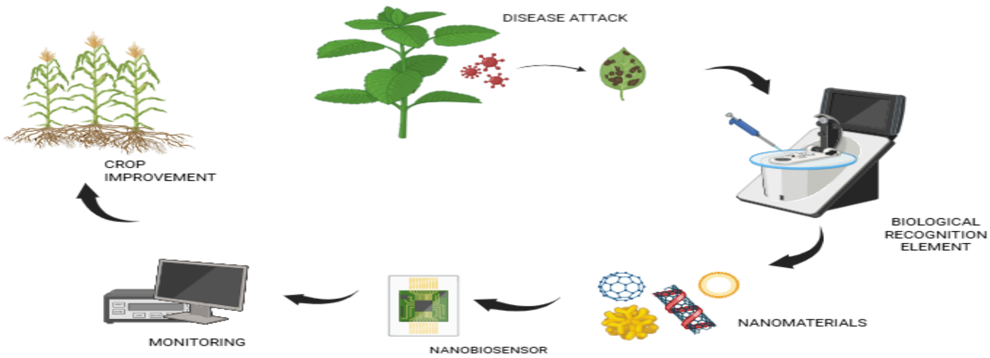

Figure 3: Pathogens are recognized and enhancing crop varieties

5.2 Detection of pesticide residue in plants

Pesticide residues found in agricultural products can pose a chemical risk for the food industry because of their toxic nature (Zhao et al., 2015). Monitoring the levels of pesticide concentration on plants can also avoid excessive application of pesticides and assist in the management of pesticides in the field. Different detection methods have been created, including biosensors utilizing surface Plasmon resonance and enzymatic sensors paired with acetylcholinesterase that use multiwalled or single-walled carbon nanotubes, to identify various pesticides like methyl parathion, parathion, fenitrothion, and paraoxon (sun et al., 2014).

A biosensor utilizing gold nanoparticles has been effectively created to identify chlorpyrifos and carbofuran at concentrations of 0.06 and 0.08 µg/dm3 (sun et al., 2014). A nano biosensor based on enzymes incorporates a combination of butyrylcholinesterase, alkaline phosphatase, and tyrosinase, utilizing Prussian blue nanoparticles that are immobilized on origami paper. This has been utilized for identifying various pesticides like atrazine, paraoxon, and 2, 4-dichlorophenoxyacetic acid. This sensor generated signals using a potentiometric method to create a paper-based nano biosensor that can enhance the development of portable nano biosensors (Arduini et al., 2019). Different herbicides, insecticides, and pesticides can be identified using the widely adopted method of electrochemical sensors. A specific nano biosensor has been created employing hollow fiber pencil-based graphite that incorporates multiwalled carbon nanotubes and Cu O nanoparticles (Gholivand et al., 2018).

5.3 Evaluation of soil quality

In farming, assessing soil quality is crucial for evaluating pH, nutrient levels, and moisture content before any agricultural activities (Monrea et al., 2015). The quality of the soil can be assessed by examining the interactions among microorganisms in the rhizosphere and the biosensor. Fertilisers, like zinc-based ones with nanoparticles, have been designed to ensure that the nutrients are released in a controlled manner to the plant roots, while feedback sensing was incorporated.

Additionally, a microelectromechanical system (MEMS) was created to monitor soil quality using miniaturised electronic circuits (Kaushal and Wani 2017). In soil, numerous nutrients are present in various forms, and each form conveys distinct signals. The existence of ammonia and elevated nitrate levels in soil suggests the activity of soil-feeding insects and indicates microbial imbalances, respectively. A wide variety of microorganisms inhabit the soil and have a significant impact on soil health and plant development. Ammonia, nitrate, and nitrite are all different forms of nitrogen (Nettleton and Peterson 2011). Lipid-based nano biosensors are utilized to identify nitrites in soil samples with a detection limit of 2.1 µ g/L (Siontorou and George 2016).

5.4 Detection of heavy metals in environment

Heavy metals have consistently been regarded as a significant threat to the well-being of both humans and animals. Ions such as Cu2+, Zn2+, Hg2+, and Cd2+, which infiltrate the body through water sources and industrial processes, affect the development of aquatic organisms in rivers, oceans, and other bodies of water, potentially putting their survival at risk (Cui et al., 2018).

The cause of this is the significant discharge of heavy metals due to the corrosion of metals, mining operations, energy generation, population increase, fossil fuel usage, plating processes, melting activities, fertilizers, and more, all of which can contaminate the environment. These activities represent the primary sources for the generation and release of heavy metals, particularly cadmium, copper, and others (Jacob et al., 2018). The detection of heavy elements and pollution-related techniques comprises of chemical approaches, enzyme-based methods, gold nanoparticles, and point quantum techniques; however, many of these methods are limited to identifying only a single metal (Tan et al., 2012).

5.5 water contamination monitoring

The quality of underground water is essential for both human health and the preservation of the environment. A range of contaminants, such as pesticides, heavy metals, and organic substances, can contaminate groundwater, posing risks to both people and the ecosystem. Applying nano biosensor technology to the detection of contaminants in groundwater is a very promising field (Steffens et al., 2022), Nano biosensor-based in-situ screening is an appealing alternative for environmental monitoring since it is quicker and more economical. Groundwater can be screened using a variety of nano biosensors, such as optical, electrochemical, and magnetic models (Ganesan and Vasudevan 2020). Due to interference from other substances in the water, electrochemical nano biosensors, which are extremely sensitive and able to identify pollutants at extremely low concentrations, can occasionally produce unreliable results (Meng et al., 2021).

6. Future trends in nano biosensors

To meet the demands in a number of fields, such as in vitro medical diagnostics, pharmaceutical discovery, and pathogen detection, the next generation of biosensor platforms must significantly improve their sensitivity and specificity. The goal of research on nano bioelectronics and biosensors is to integrate nanoelectronics, tools, and materials into inexpensive, easy-to-use, and effective sensors and biosensors. This is of interest in a number of industries, including food analysis, diagnostics, and environmental monitoring. The development of nano biosensors for agriculture has enormous potential, and computational biology including machine learning and deep learning will be essential to realizing that potential (Magarelli et al., 2023).Deep learning models can forecast crop yields, optimize fertilization and irrigation, and provide early warning of disease outbreaks by combining sensor data with weather and environmental data (Elbasi et al., 2023). Automated precision agriculture can be quickly realized by combining nano biosensors with IoT and robotics by connecting the former to wireless networks and integrating them with robotic systems; applications of smart IoT-based technologies have opened up many new potential technological advancements in all spheres of life (Haseeb et al., 2019). Automatic robotic harvesters, the harvester is guided on a sloping terrain by the control unit design of image space. Robotic harvesting of tomatoes, cherry tomatoes, cucumbers, strawberries, watermelons, and grapes is already economically viable (Fountas et al., 2020).

7. Conclusion

Nano biosensors are an emerging technology that has significant potential to enhance agricultural efficiency and ensure environmental safety. Their exceptional sensitivity, rapid response capabilities, and the ability to identify pathogens, nutrients, toxins, and pollutants make them essential for real-time surveillance. In the agricultural sector, nano biosensors aid in early disease detection, evaluating soil quality, and managing nutrients with precision, allowing farmers to make prompt and well-informed choices. Likewise, in environmental monitoring, these sensors facilitate the precise identification of heavy metals, pesticides, and new contaminants, helping to maintain healthier ecosystems. Despite notable advancements, hurdles such as sensor reliability, mass production, durability in field conditions, and obtaining regulatory approval continue to hinder widespread use. Combining nano biosensors with IoT technology, mobile applications, and AI-driven data systems can improve predictive capabilities and enable ongoing monitoring. Future studies should concentrate on creating affordable, multifunctional, and environmentally friendly sensor systems that can be deployed in the field. In summary, nano biosensors show tremendous potential to advance sustainable farming, enhance environmental wellbeing, and support global food security.

Reference

1. Sharon, M., Choudhary, A. K., & Kumar, R. (2010). Nanotechnology in agricultural diseases and food safety. Journal of phytology, 2(4).
2. Johnson, M. S., Sajeev, S., & Nair, R. S. (2021, March). Role of Nano sensors in agriculture. In 2021 international conference on computational intelligence and knowledge economy (ICCIKE) (pp. 58-63). IEEE.
3. Joseph, T., & Morrison, M. (2006). Nanotechnology in agriculture and food: a nano forum report. Nano forum. org.
4. Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in agriculture: which innovation potential does it have?. Frontiers in Environmental Science, 4, 20.
5. Periakaruppan, R., Romanovski, V., Thirumalaisamy, S. K., Palanimuthu, V., Sampath, M. P., Anilkumar, A., ... & Selvaraj, K. S. V. (2023). Innovations in modern nanotechnology for the sustainable production of agriculture. Chem Engineering, 7(4), 61
6. Dar, F. A., Qazi, G., & Pirzadah, T. B. (2020). Nano-biosensors: NextGen diagnostic tools in agriculture. In Nanobiotechnology in agriculture: an approach towards sustainability (pp. 129-144). Cham: Springer International Publishing.
7. Vo-Dinh, T., & Cullum, B. (2000). Biosensors and biochips: advances in biological and medical diagnostics. Fresenius' journal of analytical chemistry, 366(6), 540-551.

8. Huang, X., Zhu, Y., & Kianfar, E. (2021). Nano biosensors: properties, applications and electrochemical techniques. Journal of Materials Research and Technology, 12, 1649-1672.
9. Schaertel, B. J., & Firstenberg-Eden, R. (1988). Biosensors in the food industry: present and future. Journal of food protection, 51(10), 811-820.
10. Hock B, Seifert M, Kramer K (2002) Engineering receptors and antibodies for biosensors. Biosensor Bio electron 17(3):239–249.
11. Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. Arabian journal of chemistry, 12(7), 908-931.
12. Saini, R. K., Bagri, L. P., & Bajpai, A. K. (2017). New pesticides and soil sensors. Netherlands: Elsevier.
13. Silme, R. S., & Baysal, Ö. (2020). A missing dilemma on nanoparticle producer microorganisms. In Biogenic Nano-Particles and their Use in Agro-ecosystems (pp. 407-429). Singapore: Springer Singapore.
14. McConnell, E. M., Nguyen, J., & Li, Y. (2020). Aptamer-based biosensors for environmental monitoring. Frontiers in chemistry, 8, 434.
15. Chiu, T. C., & Huang, C. C. (2009). Aptamer-functionalized nano-biosensors. Sensors, 9(12), 10356-10388.
16. Wujcik, E. K., Wei, H., Zhang, X., Guo, J., Yan, X., Sutrave, N., ... & Guo, Z. (2014). Antibody nano sensors: a detailed review. Rsc Advances, 4(82), 43725-43745.
17. Purohit, B., Vernekar, P. R., Shetti, N. P., & Chandra, P. (2020). Biosensor nanoengineering: Design, operation, and implementation for biomolecular analysis. Sensors International, 1, 100040.
18. Braun, T., Ghatkesar, M. K., Backmann, N., Grange, W., Boulanger, P., Letellier, L.,& Hegner, M. (2009). Quantitative time-resolved measurement of membrane protein–ligand interactions using microcantilever array sensors. Nature nanotechnology, 4(3), 179-185.
19. Polacheck, W. J., & Chen, C. S. (2016). Measuring cell-generated forces: a guide to the available tools. Nature methods, 13(5), 415-423.
20. Rodahl, M., Höök, F., Krozer, A., Brzezinski, P., & Kasemo, B. (1995). Quartz crystal microbalance setup for frequency and Q-factor measurements in gaseous and liquid environments. Review of Scientific Instruments, 66(7), 3924-3930.
21. Zhu, S., Song, Y., Zhao, X., Shao, J., Zhang, J., & Yang, B. (2015). The photoluminescence mechanism in carbon dots (graphene quantum dots, carbon nanodots, and polymer dots): current state and future perspective. Nano research, 8(2), 355-381.
22. Cheng, Y. T., Rodak, D. E., Wong, C. A., & Hayden, C. A. (2006). Effects of micro-and nano-structures on the self-cleaning behaviour of lotus leaves. Nanotechnology, 17(5), 1359.
23. Hammond, J. L., Formisano, N., Estrela, P., Carrara, S., & Tkac, J. (2016). Electrochemical biosensors and nano biosensors. Essays in biochemistry, 60(1), 69-80.
24. Bakirhan, N. K., Topal, B. D., Ozcelikay, G., Karadurmus, L., & Ozkan, S. A. (2022). Current advances in electrochemical biosensors and nano biosensors. Critical reviews in analytical chemistry, 52(3), 519-534.
25. Hameed, S., Munawar, A., Khan, W. S., Mujahid, A., Ihsan, A., Rehman, A., & Bajwa, S. Z. (2017). Assessing manganese nanostructures based carbon nanotubes composite for the highly

sensitive determination of vitamin C in pharmaceutical formulation. Biosensors and Bioelectronics, 89, 822-828.

26. Qu, S., Wang, X., Lu, Q., Liu, X., & Wang, L. (2012). A biocompatible fluorescent ink based on water-soluble luminescent carbon nanodots. Angewandte Chemie-International Edition, 51(49), 12215.
27. Lee, S. H., Heng, D., Ng, W. K., Chan, H. K., & Tan, R. B. (2011). Nano spray drying: a novel method for preparing protein nanoparticles for protein therapy. International journal of pharmaceutics, 403(1-2), 192-200.
28. Kumar, A., Choudhary, A., Kaur, H., Mehta, S., & Husen, A. (2021). Metal-based nanoparticles, sensors, and their multifaceted application in food packaging. Journal of Nanobiotechnology, 19(1), 256.
29. Kumar, R., Kumar, P., Singh, M., Bhatia, R., Bala, J., Sidhu, H. S., & Sindhu, A. (2025). Optical Nano biosensors in Precision Agriculture. In Nano biosensors for Crop Monitoring and Precision Agriculture (pp. 29-49). Singapore: Springer Nature Singapore.
30. Zhu, W., Li, L., Zhou, Z., Yang, X., Hao, N., Guo, Y., & Wang, K. (2020). A colorimetric biosensor for simultaneous ochratoxin A and aflatoxins B1 detection in agricultural products. Food Chemistry, 319, 126544.
31. Liu, Y., Li, J., Wang, G., Zu, B., & Dou, X. (2020). One-step instantaneous detection of multiple military and improvised explosives facilitated by colorimetric reagent design. Analytical Chemistry, 92(20), 13980-13988.
32. Yokobori, S., Shimazaki, J., Kaneko, H., Asai, H., Kanda, J., Takauji, S., & Yokota, H. (2025). The feasibility of point-of-care testing for initial urinary liver fatty acid-binding protein to estimate severity in severe heatstroke. Scientific Reports, 15(1), 5255.
33. Zhang, P., Sun, T., Rong, S., Zeng, D., Yu, H., Zhang, Z.,& Pan, H. (2019). A sensitive amperometric AChE-biosensor for organophosphate pesticides detection based on conjugated polymer and Ag-rGO-NH2 nanocomposite. Bioelectrochemistry, 127, 163-170.
34. Nguyen, Q. H., & Kim, M. I. (2020). Nanomaterial-mediated paper-based biosensors for colorimetric pathogen detection. TrAC Trends in Analytical Chemistry, 132, 116038.
35. Pohanka, M. (2018). Overview of piezoelectric biosensors, immunosensors and DNA sensors and their applications. Materials, 11(3), 448.
36. Selvarajan, S., Alluri, N. R., Chandrasekhar, A., & Kim, S. J. (2017). Unconventional active biosensor made of piezoelectric BaTiO3 nanoparticles for biomolecule detection. Sensors and Actuators B: Chemical, 253, 1180-1187.
37. Malekzad, H., Sahandi Zangabad, P., Mirshekari, H., Karimi, M., & Hamblin, M. R. (2017). Noble metal nanoparticles in biosensors: recent studies and applications. Nanotechnology reviews, 6(3), 301-329.
38. Antonacci, A., Arduini, F., Moscone, D., Palleschi, G., & Scognamiglio, V. (2018). Nanostructured (Bio) sensors for smart agriculture. TrAC Trends in Analytical Chemistry, 98, 95-103.
39. Foroughi, M. M., Jahani, S., Aramesh-Boroujeni, Z., Dolatabad, M. R., & Shahbazkhani, K. (2021). Synthesis of 3D cubic of Eu3+/Cu2O with clover-like faces nanostructures and their application as an electrochemical sensor for determination of antiretroviral drug nevirapine. Ceramics International, 47(14), 19727-19736.

40. Xiang, C., Li, R., Adhikari, B., She, Z., Li, Y., & Kraatz, H. B. (2015). Sensitive electrochemical detection of Salmonella with chitosan–gold nanoparticles composite film. Talanta, 140, 122-127.
41. Santos, A. O., Vaz, A., Rodrigues, P., Veloso, A. C., Venâncio, A., & Peres, A. M. (2019). Thin films sensor devices for mycotoxins detection in foods: Applications and challenges. Chemosensors, 7(1), 3.
42. Mohammadi, A., Heydari-Bafrooei, E., Foroughi, M. M., & Mohammadi, M. (2020). Electrochemical aptasensor for ultrasensitive detection of PCB77 using thionine-functionalized MoS2-rGO nanohybrid. Microchemical Journal, 155, 104747.
43. Garg, R., Garg, R., Eddy, N. O., Almohana, A. I., Almojil, S. F., Khan, M. A., & Hong, S. H. (2022). Biosynthesized silica-based zinc oxide nanocomposites for the sequestration of heavy metal ions from aqueous solutions. Journal of King Saud University-Science, 34(4), 101996.
44. V.K. Yata, B.C. Tiwari and I. Ahmad, Environ. Chem. Lett. 16, 79 (2018). doi:10.1007/s10311-017-0666-7.
45. Cardoso, R. M., Pereira, T. S., Facure, M. H., dos Santos, D. M., Mercante, L. A., Mattoso, L. H., & Correa, D. S. (2022). Current progress in plant pathogen detection enabled by nanomaterials-based (bio) sensors. Sensors and Actuators Reports, 4, 100068.
46. Kubavat, D., Trivedi, K., Vaghela, P., Prasad, K., Vijay Anand, G. K., Trivedi, H., & Ghosh, A. (2020). Characterization of a chitosan-based sustained release nanofertilizer formulation used as a soil conditioner while simultaneously improving biomass production of Zea mays L. Land Degradation & Development, 31(17), 2734-2746.
47. Trzcińska-Wencel, J., Wypij, M., Rai, M., & Golińska, P. (2023). Biogenic nanosilver bearing antimicrobial and antibiofilm activities and its potential for application in agriculture and industry. Frontiers in Microbiology, 14, 1125685.
48. Pandey, K., Anas, M., Hicks, V. K., Green, M. J., & Khodakovskaya, M. V. (2019). Improvement of commercially valuable traits of industrial crops by application of carbon-based nanomaterials. Scientific reports, 9(1), 19358.
49. Gao, M., Chang, X., Yang, Y., & Song, Z. (2020). Foliar graphene oxide treatment increases photosynthetic capacity and reduces oxidative stress in cadmium-stressed lettuce. Plant Physiology and Biochemistry, 154, 287-294.
50. Kumaraswamy, R. V., Kumari, S., Choudhary, R. C., Pal, A., Raliya, R., Biswas, P., & Saharan, V. (2018). Engineered chitosan based nanomaterials: Bioactivities, mechanisms and perspectives in plant protection and growth. International journal of biological macromolecules, 113, 494-506.
51. Manjunatha, S. B., Biradar, D. P., & Aladakatti, Y. R. (2016). Nanotechnology and its applications in agriculture: A review. J farm Sci, 29(1), 1-13.
52. Mittal, D., Kaur, G., Singh, P., Yadav, K., Ali, S.A., 2020. Nanoparticle-based sustainable agriculture and food science: recent advances and future outlook. Front. Nanotechnol. 2, 579954.
53. Shang, Y., Hasan, M. K., Ahammed, G. J., Li, M., Yin, H., & Zhou, J. (2019). Applications of nanotechnology in plant growth and crop protection: a review. Molecules, 24(14), 2558.
54. Khiyami, M. A., Almoammar, H., Awad, Y. M., Alghuthaymi, M. A., & Abd-Elsalam, K. A. (2014). Plant pathogen nanodiagnostic techniques: forthcoming changes?. Biotechnology & Biotechnological Equipment, 28(5), 775-785.

55. Ali, Q., Ahmar, S., Sohail, M. A., Kamran, M., Ali, M., Saleem, M. H., & Ali, S. (2021). Research advances and applications of biosensing technology for the diagnosis of pathogens in sustainable agriculture. Environmental Science and Pollution Research, 28(8), 9002-9019.
56. Dyussembayev, K., Sambasivam, P., Bar, I., Brownlie, J. C., Shiddiky, M. J., & Ford, R. (2021). Biosensor technologies for early detection and quantification of plant pathogens. Frontiers in Chemistry, 9, 636245.
57. Cebula, Z., Żołędowska, S., Dziąbowska, K., Skwarecka, M., Malinowska, N., Białobrzeska, W.,& Nidzworski, D. (2019). Detection of the plant pathogen Pseudomonas syringae pv. Lachrymans on antibody-modified gold electrodes by electrochemical impedance spectroscopy. Sensors, 19(24), 5411.
58. Wu, L., Lu, X., Fu, X., Wu, L., & Liu, H. (2017). Gold nanoparticles dotted reduction graphene oxide nanocomposite based electrochemical aptasensor for selective, rapid, sensitive and congener-specific PCB77 detection. Scientific reports, 7(1), 5191.
59. Khaledian, S., Nikkhah, M., Shams-bakhsh, M., & Hoseinzadeh, S. (2017). A sensitive biosensor based on gold nanoparticles to detect Ralstonia solanacearum in soil. Journal of General Plant Pathology, 83(4), 231-239.
60. Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K., & Duhan, S. (2017). Nanotechnology: The new perspective in precision agriculture. Biotechnology reports, 15, 11-23.
61. Kaushal, M., & Wani, S. P. (2017). Nanosensors: frontiers in precision agriculture. In Nanotechnology: An agricultural paradigm (pp. 279-291). Singapore: Springer Singapore.
62. Zhao, G., Guo, Y., Sun, X., & Wang, X. (2015). A system for pesticide residues detection and agricultural products traceability based on acetylcholinesterase biosensor and internet of things. International Journal of Electrochemical Science, 10(4), 3387-3399.
63. Sun, D., Hussain, H. I., Yi, Z., Siegele, R., Cresswell, T., Kong, L., & Cahill, D. M. (2014). Uptake and cellular distribution, in four plant species, of fluorescently labeled mesoporous silica nanoparticles. Plant cell reports, 33(8), 1389-1402.
64. Arduini, F., Cinti, S., Caratelli, V., Amendola, L., Palleschi, G., & Moscone, D. (2019). Origami multiple paper-based electrochemical biosensors for pesticide detection. Biosensors and Bioelectronics, 126, 346-354.
65. Gholivand, M. B., Akbari, A., & Norouzi, L. (2018). Development of a novel hollow fiber-pencil graphite modified electrochemical sensor for the ultra-trace analysis of glyphosate. Sensors and Actuators B: Chemical, 272, 415-424.
66. Bindraban, P. S., Monreal, C. M., DeRosa, M., Mallubhotla, S. C., & Dimkpa, C. O. (2015). The Application of Nanotechnology for Micronutrients in Soil-Plant Systems.
67. Nettleton, W. D., & Peterson, F. F. (2011). Landform, soil, and plant relationships to nitrate accumulation, Central Nevada. Geoderma, 160(3-4), 265-270.
68. Siontorou, C. G., & Georgopoulos, K. N. (2016). A biosensor platform for soil management: the case of nitrites. Journal of Cleaner Production, 111, 133-142.
69. Cui, Z., Luan, X., Jiang, H., Li, Q., Xu, G., Sun, C., ... & Huang, W. E. (2018). Application of a bacterial whole cell biosensor for the rapid detection of cytotoxicity in heavy metal contaminated seawater. Chemosphere, 200, 322-329.

70. Jacob, J. M., Karthik, C., Saratale, R. G., Kumar, S. S., Prabakar, D., Kadirvelu, K., & Pugazhendhi, A. (2018). Biological approaches to tackle heavy metal pollution: a survey of literature. Journal of environmental management, 217, 56-70.
71. Tan, E., Yin, P., Lang, X., Zhang, H., & Guo, L. (2012). A novel surface-enhanced Raman scattering nanosensor for detecting multiple heavy metal ions based on 2-mercaptoisonicotinic acid functionalized gold nanoparticles. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 97, 1007-1012.
72. Steffens, C., Ballen, S. C., Scapin, E., da Silva, D. M., Steffens, J., & Jacques, R. A. (2022). Advances of nanobiosensors and its application in atrazine detection in water: A review. Sensors and Actuators Reports, 4, 100096.
73. Ganesan, S., & Vasudevan, N. (2020). Genetically modified microbial biosensor for detection of pollutants in water samples. In Environmental Biotechnology Vol. 3 (pp. 85-103). Cham: Springer International Publishing.
74. Meng, Z., Guo, S., Zhou, Y., Li, M., Wang, M., & Ying, B. (2021). Applications of laboratory findings in the prevention, diagnosis, treatment, and monitoring of COVID-19. Signal transduction and targeted therapy, 6(1), 316.
75. Magarelli, G., Freire, A. M., & Silva, L. P. (2023). Electrochemical sensors coupled with machine learning for food safety and quality inspection. In Food quality analysis (pp. 171-200). Academic Press.
76. Elbasi, E., Zaki, C., Topcu, A. E., Abdelbaki, W., Zreikat, A. I., Cina, E., ... & Saker, L. (2023). Crop prediction model using machine learning algorithms. Applied Sciences, 13(16), 9288.
77. Haseeb, K., Almogren, A., Islam, N., Ud Din, I., & Jan, Z. (2019). An energy-efficient and secure routing protocol for intrusion avoidance in IoT-based WSN. Energies, 12(21), 4174.
78. Song, J., Xu, L., Zhou, C., Xing, R., Dai, Q., Liu, D., & Song, H. (2013). Synthesis of graphene oxide based Cu O nanoparticles composite electrode for highly enhanced nonenzymatic glucose detection. ACS applied materials & interfaces, 5(24), 12928-12934.
79. Khoshhesab, Z. M. (2015). Simultaneous electrochemical determination of acetaminophen, caffeine and ascorbic acid using a new electrochemical sensor based on Cu O–graphene nanocomposite. RSC advances, 5(115), 95140-95148.
80. Cai, Z., Ye, Y., Wan, X., Liu, J., Yang, S., Xia, Y., & He, Q. (2019). Morphology–dependent electrochemical sensing properties of iron oxide–graphene oxide nanohybrids for dopamine and uric acid. Nanomaterials, 9(6), 835.
81. AL-Mokaram, A. M. A. A., Yahya, R., Abdi, M. M., & Mahmud, H. N. M. E. (2016). One-step electrochemical deposition of Polypyrrole–Chitosan–Iron oxide nanocomposite films for non-enzymatic glucose biosensor. Materials Letters, 183, 90-93.
82. Vu, Q. K., Tran, Q. H., Vu, N. P., Anh, T. L., Le Dang, T. T., Matteo, T., & Nguyen, T. H. H. (2021). A label-free electrochemical biosensor based on screen-printed electrodes modified with gold nanoparticles for quick detection of bacterial pathogens. Materials Today Communications, 26, 101726.
83. Akhtar, N., Metkar, S. K., Girigoswami, A., & Girigoswami, K. (2017). ZnO nanoflower based sensitive nano-biosensor for amyloid detection. Materials Science and Engineering: C, 78, 960-968.

84. James, A., Franco, F., Merca, E. M., Rodriguez, S., Johny, F., Balidon-Veronica, P.,& Fernando, L. M. (2019). DNA based electrochemical nanobiosensor for the detection of Phytophthora palmivora causing black pod rot in cacao (Theobroma cacao L.) pods. Physiol. Mol. Plant Pathol, 107, 14-20.
85. Antonacci, A., Arduini, F., Moscone, D., Palleschi, G., & Scognamiglio, V. (2018). Nanostructured (Bio) sensors for smart agriculture. TrAC Trends in Analytical Chemistry, 98, 95-103.
86. Sharma, S., Rana, V. S., Pawar, R., Lakra, J., & Racchapannavar, V. (2021). Nanofertilizers for sustainable fruit production: a review. Environmental Chemistry Letters, 19(2), 1693-1714.
87. Bahadır, E. B., & Sezgintürk, M. K. (2017). Biosensor technologies for analyses of food contaminants. In Nanobiosensors (pp. 289-337). Academic Press.
88. Meraat, R., Issazadeh, K., Abdolahzadeh Ziabari, A., & Faezi Ghasemi, M. (2020). Rapid Detection of Escherichia coli by β-Galactosidase Biosensor Based on ZnO NPs and MWCNTs: A Comparative Study. Current Microbiology, 77(10).
89. Zhang, P., Sun, T., Rong, S., Zeng, D., Yu, H., Zhang, Z., & Pan, H. (2019). A sensitive amperometric AChE-biosensor for organophosphate pesticides detection based on conjugated polymer and Ag-rGO-NH2 nanocomposite. Bioelectrochemistry, 127, 163-170.