Nanofabricated Materials as Nanobiosensor: A Brief Overview

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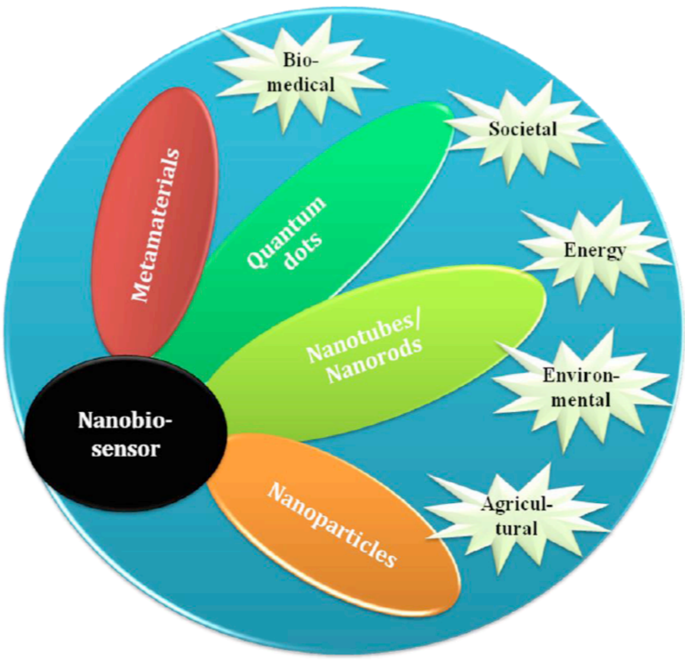
Abstract: Nanofabricated materials have become a revolutionary foundation in the creation of nanobiosensors, facilitating the highly sensitive, selective, and quick identification of biological and chemical analytes. Advancements in nanotechnology have enabled the fabrication of materials with precise size, shape, and surface characteristics at the nanoscale, greatly enhancing the efficacy of biosensing devices. Materials include nanowires, nanotubes, quantum dots, graphene, metallic nanoparticles, and thin films possess distinctive electrical, optical, and catalytic characteristics, which are utilized in signal transduction and amplification processes. These tailored nanostructures enhance biomolecule immobilization and stability while facilitating label-free, real-time monitoring with ultra-low detection limits. Nanobiosensors utilizing nanofabricated materials have shown utility in various domains, such as medical diagnostics, environmental monitoring, food safety, and drug development. Furthermore, the integration of microfluidics and wearable devices is propelling the advancement of point-of-care platforms for personalized healthcare. Notwithstanding significant advancements, obstacles including reproducibility, large-scale production, biocompatibility, and regulatory approval persist. This concise summary underscores the significance of nanofabricated materials in the progression of biosensing technologies, accentuating its capacity to transform diagnostics and monitoring systems via shrinking, multiplexing, and improved analytical performance.

Keywords: Nanomaterials, Nanobiosensors, Medical and Clinical Diagnostics, Environmental applications.



Graphical representation of types and applications of nanobiosensor

INTRODUCTION

Engineered structures with characteristics on the nanoscale typically fewer than 100 nanometers—are known as nanofabricated materials. The physical, chemical, electrical, and optical properties of these materials can be precisely controlled because of the use of nanofabrication techniques. Their special qualities make them indispensable in a variety of fields, ranging from environmental research and medicine to electronics and energy. The method of creating structures with nanoscale accuracy is known as nanofabrication (Kulkarni *et al*., 2022; Saha, 2024). It uses methods from engineering, physics, chemistry, and materials science to make devices and patterns that is just a few nanometers across. In order to get the desired nanoscale features, "top-down nanofabrication" (*e.g*., photolithography, electron beam lithography) begins with larger bulk materials and gradually removes parts (Kulkarni *et al*., 2022; Naresh and Lee, 2021). This method is similar to sculpting in that it requires removing material from a block to

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produce a complex structure. A technique called "bottom-up nanofabrication" builds nanostructures from the atomic or molecular level by assembling basic building components (atoms, molecules, or nanoparticles) into more complex structures (Singh, 2011). It mimics natural processes such as crystal formation and biological self-assembly. This approach is more like "building" than "sculpting" (top-down). The production of homogenous, highly ordered nanostructures with fewer defects and less material waste is often made possible by it (Singh *et al*., 2023).

In recent years, nanotechnology has emerged as a transformative force in the development of next-generation biosensors. The biological sensing element in biosensors is a device that transforms a chemical or biological condition into an electrical signal. Micromachining, thin film technology, microelectronics, molecular electronics, and information technologies can all be used to realize the essential elements of a biosensor system, including sample handling and manipulation, amplification, transduction, biological recognition and electronic signal processing (Chaudhary *et al*., 2021; Kundu *et al*., 2022; Parameswari *et al*., 2024). There are several types of nanofabricated materials, which is synthesized and used as a biosensor for various prospective. The most common nanofabricated materials includes nanoparticles, nanowires, nanorods, nanotubes, graphene based materials, quantum dots, thin films and metamaterials etc (Figure **1**) (Kulkarni *et al*., 2022; Naresh and Lee, 2021; Singh *et al*., 2023).

Nanoparticles are increasingly used in biosensors due to their unique physical and chemical properties at the nanoscale. Their high surface-to-volume ratio, ability to bind to biological molecules, and tunable optical/electronic properties make them ideal for sensitive and specific detection of biological targets (Saha *et al*., 2021; Saha *et al*., 2024). Presently, the nanoscale field of materials science is dominated by nanowires, which resemble extremely thin wires, and nanotubes, which resemble cylindrical nanostructures. Prototypes of nanowires and nanotubes include bismuth nanowires and carbon nanotubes. Both nano-materials hold great potential for real-world applications and provide novel ideas to the field of nanoscience (Khalkho *et al*., 2021; Kundu *et al*., 2022). The role of nanoparticles as nanobiosensor is listed in Table **1**.

Thin films may be described as a "two-dimensional" material in which the surface-to-volume ratio significantly increases (up to 106) as the third dimension, thickness, gets so thin (*i.e.*, 1 µm to 1 nm). Moreover, thin film methods may produce films with varying chemical compositions and morphologies, imparting distinctive features relative to bulk materials. The predominant influence of surfaces in thin films enables them to address stability issues at various interfaces (Tvarozek *et al*., 1998).

Among various nanomaterials, graphene has gained particular attention due to its exceptional physicochemical properties. Graphene is a two-dimensional sheet of carbon atoms arranged in a honeycomb lattice that exhibits remarkable electrical conductivity, high mechanical strength, large specific surface area, and excellent biocompatibility. These attributes make graphene an ideal platform for the immobilization of biorecognition elements (*e.g.*, antibodies, enzymes, nucleic acids) and for enhancing signal transduction in biosensors (Sinha *et al*., 2023; Sinha *et al*., 2024).

Graphene-based biosensors leverage these properties to achieve highly sensitive and selective detection of a wide array of target biomolecules, including glucose, DNA, RNA, proteins, neurotransmitters, and pathogens (Chaudhary *et al*.,

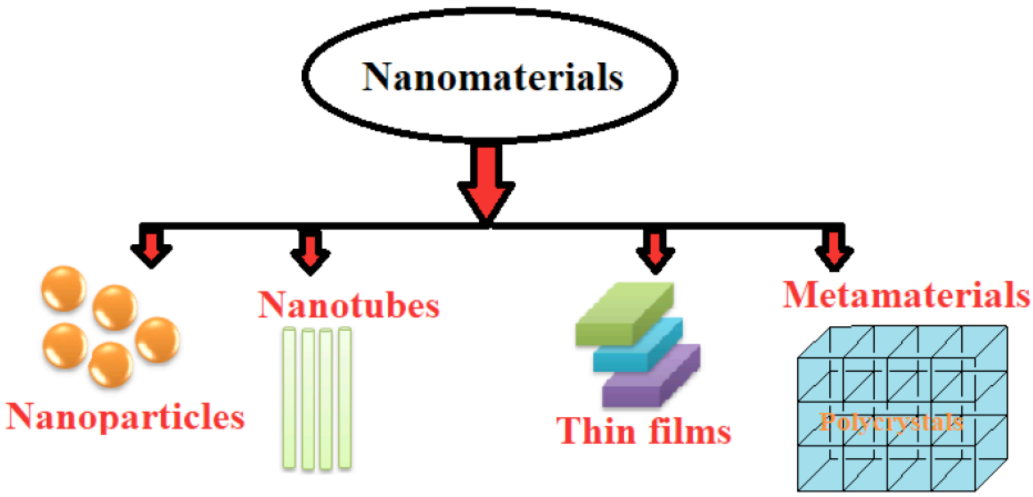

Figure 1: Types of nanomaterial biosensor.

Table 1: Roles of Nanoparticles in Biosensors (Kulkarni etr al., 2022)

Role	Description
Signal transduction	Enhance the measurable signal (*e.g.*, fluorescence, conductivity)
Surface functionalization	Attach to biological molecules (antibodies, DNA, enzymes) for selective detection
Catalysis	Act as nanozymes (nanomaterial-based enzymes) to trigger a detectable reaction
Target delivery	Bind and concentrate the analyte at the sensor surface

Table 2: Nanobiosensor Applications in Different Area

Application Area	Biomolecules Detected	Example
Medical Diagnostics	DNA, RNA, miRNA, proteins, glucose	Detection of BRCA1 gene, dopamine in Parkinson's
Infectious Disease	Viral proteins, bacterial toxins	SARS-CoV-2, E. coli
Food Safety	Pathogens, pesticides	Listeria monocytogenes, organophosphates
Environmental Monitoring	Heavy metals, toxins	Pb^{2+}, Hg^{2+}, bisphenol A

2021; Sinha *et al*., 2024). Moreover, the versatility of graphene derivatives—such as graphene oxide (GO) and reduced graphene oxide (rGO)—enables fine-tuned surface chemistry and functionalization, which are crucial for developing specific and robust sensing platforms (Chaudhary *et al*., 2021).

The integration of graphene into various sensing modalities, such as electrochemical, optical, and field-effect transistor (FET)-based biosensors, has led to significant improvements in detection performance. In particular, graphene FET biosensors have demonstrated ultrafast, label-free detection capabilities at ultralow concentrations, holding great promise for clinical diagnostics, especially in detecting disease biomarkers such as cancer antigens, viral proteins, and micro RNAs (Kulkarni etr al., 2022).

Different procedures can be used to create nonmaterials in a variety of ways. Typically, nanostructures like nanowires, nanoclusters, nanorods, and nanotubes can have a diameter of 1 nm to 100 nm. A variety of techniques can be used to create nanomaterials, depending on the methodology, temperature, duration, and reagent concentration. Furthermore, by creating molecules from micro to nanomaterials or fading their size, these structures can be produced (Kulkarni etr al., 2022; Naresh and Lee, 2021; Saha *et al*., 2021). These approaches enable the diffusion and synthesis of nanomaterials and fluid particles. Many methods used in the synthesis of nanomaterials are illustrated in Figure **2**.

NANOBIOSENSOR

The exploration of nanomaterials, including nanotubes, nanowires, and quantum dots, in the context of biosensor medical diagnostic devices is currently underway. The advancements in the characteristics of nanomaterials at the nanoscale have led to the rapid emergence of new devices, such as smart biosensors, capable of detecting minute concentrations of specific bio-samples for real-time monitoring (Kulkarni etr al., 2022; Naresh and Lee, 2021; Saha *et al*., 2021). In this context, nanomaterials are often utilized as transducer resources, playing a crucial role in the advancement of biosensors. Biosensors can be classified into five distinct categories: (i) analyte, (ii) bioreceptor, (iii) electrical interface, (iv) transducer, and (v) biosensors.

Biosensors can analyze many analytes, including dietary samples, bodily fluids, and cell cultures. Upon the introduction of the test substance into a buffer solution, its constituents are identified (glucose, saliva, lactose, creatinine, and ammonia). Biorecognition generates a signal during the interface between the sample and components. Simultaneously, the transducer converts a biorecognition signal into a quantifiable electrical signal, indicating the presence of a biochemical or biological target. The interactions between the analyte and bioreceptor correlate with the electrical or optical signals produced by the transducers, which can connect to a smartphone through a cloud database for real-time data access and storage, presented in numerical, graphical, or tabular formats (Gavrilaș *et al*., 2022).

Many nanomaterials' electrical and mechanical characteristics have been investigated recently in order to use them for improved biological signal processing. Thin films made of crystalline matter, nanowires, nanotubes, and nanorods are a few widely used nanomaterials in sensing applications. Amperometric

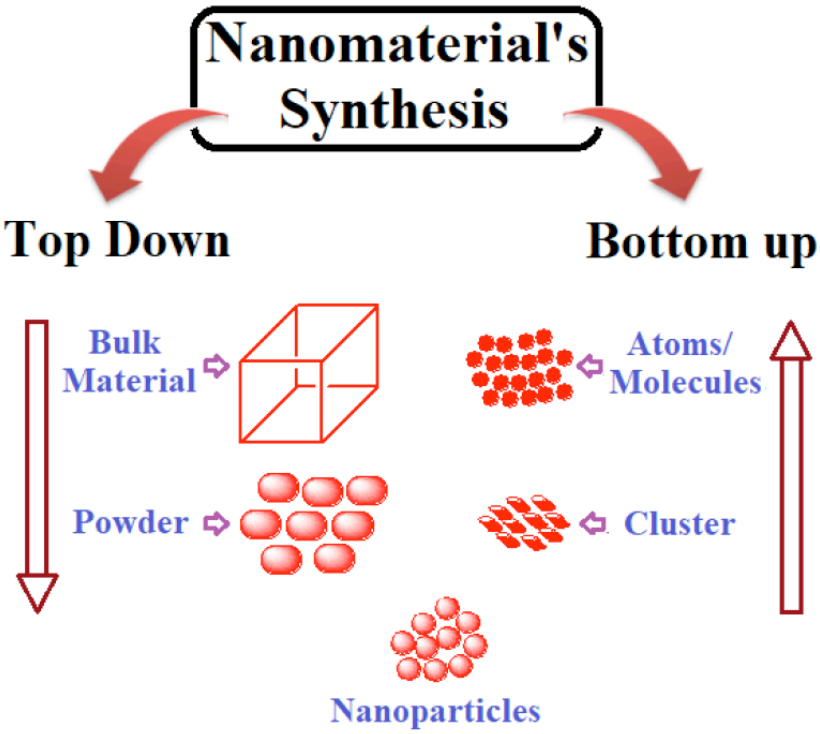

Figure 2: Methods of synthesis of nanomaterials.

devices can be used for enzyme-based glucose sensing, quantum dots (QDs) as fluorescent agents for binding detection, and bioconjugated nanomaterials for directed biomolecular detection. By combining with antibodies, these colloidal nanoparticles can be used for immunosensing and immunolabeling applications. These materials can also be employed to enhance electron microscope detections. Nanomaterials based on metals are also especially well suited for optical and electrical applications (Kundu *et al*., 2022; Saha *et al*., 2021). They can be utilized to detect nucleic acid sequences by properly utilizing their optoelectronic properties. Numerous nanomaterials have been described in order to examine their characteristics and potential topical uses in biosensors. The biosensor's linearity, sensitivity, selectivity, and response time are traits that improve efficiency (Gavrilaș *et al*., 2022; Soldatkin *et al*., 2022).

Studies indicate a steady increase in the number of nanomaterials that can be used to enhance the sensitivity and capability of multi-detection by implementing transducer or receptor operation. These nanomaterials include, among others, biological nanomaterials, nanoparticles, nanotubes, and quantum dots (Giepmans *et al*., 2006; Kulkarni *et al*., 2021). The transducer, the bio-recognition component, or both may be supported by these. Biochemical and biological research fields have been transformed by nanosensors, nanoprobes, and other nanodevices that allow for the rapid analysis of many substances *in vivo*.

In the last few years, a vast array of nanomaterials with a variety of properties have surfaced, such as small size, speed, shorter electron travel distances, lower voltages, and lower power (Naresh and Lee, 2021; Umapathi *et al*., 2019). As a result of remarkable developments in nanotechnology, nanomaterials such

Table 3: Different Nanobiosensors (Nanomaterials) and their Properties

S.No.	Name of Nanomaterials	Properties
1.	Nanoparticles	High loading and immobilize efficiency, Good Catalytic property
2.	Nanorods	Plasmonic material, Size tunable energy regulation
3.	Nanowires	Highly versatile, Good charge conduction, Good electrical and sensing properties
4.	Carbon nanotubes	Imparts physical and mechanical properties to enhance conductivity and resistance to temperature
5.	Metal oxide nanomaterials	Antimicrobial, Ability of photocatalytic, UV absorption, Better electrical conductivity
6.	Quantum dots	Excellent fluorescence, Size tunable bandwidth energy, Confinement of charge carriers

as nanoparticles, nanorods, thin films, magnetic nanomaterials, quantum dots and carbon materials are now employed to improve the electrochemical signals of biocatalytic processes (Table **3**) that occur at the electrode and electrolyte collision. The different types of functionalized nanomaterials attached with biomolecules like amino acids, proteins, DNA etc. are also been used as biosensors (Umapathi *et al*., 2019).

APPLICATIONS OF NANOBIOSENSORS

Medical and Clinical Diagnostics

1. Detection of Cancer Biomarkers (*e.g.*, PSA, HER2, microRNAs)

Nanomaterials (*e.g*., gold nanoparticles, graphene, metal–organic frameworks, and 2D semiconductors) amplify biorecognition events by (i) enlarging effective surface area for dense immobilization of capture probes, (ii) accelerating charge/energy transfer for stronger transduction, and (iii) enabling field-effect or plasmonic confinement to push limits of detection (LOD) into pico- to femto-scale ranges—often within minutes and from microliter volumes. These advantages are particularly impactful for early cancer detection from minimally processed serum, plasma, or urine (Rotake et. al., 2025; Kang et. al.,2021).

Prostate-Specific Antigen (PSA): Electrochemical nanobiosensors are the most mature class for PSA, frequently combining conductive nanocarbons (graphene, carbon nanotubes, carbon quantum dots) with noble metals (Au, Ag) to create high-surface, high-conductivity interfaces for antibody or aptamer capture.

Au/C nanohybrids & aptamers: Decorating electrodes with Au nanoparticles (AuNPs) and carbon quantum dots or reduced graphene oxide improves electron transfer and boosts probe loading, enabling sub-nanogram per milliliter PSA quantification. For example, aptamer-based formats with Au/CQD interfaces report broad linear ranges and clinically relevant LODs in serum (Antiochia, 2020)

Benchmark sensitivity: As a reference point, a (non-nano) but widely cited nanostructure-assisted aptasensor achieved an LOD of ~0.04 ng mL^{-1} (40 pg mL^{-1}), within the diagnostic zone used for risk stratification around 4 ng mL^{-1}, highlighting how nanointerfaces help close the gap between lab assays and point-of-care (POC) devices (Sousa et. al., 2024)

Paper & screen-printed platforms: Screen-printed Au electrodes and paper-based devices are increasingly integrated with nanomaterials to lower cost and simplify readout, moving toward POC PSA tests while maintaining pg–ng mL^{-1} sensitivity. (Tang and Hewlett, 2010)

Design takeaways. (1) Use AuNPs or hybrid Au–carbon scaffolds to raise electroactive surface area and support dense aptamer/antibody layers; (2) favor differential pulse or square-wave voltammetry for signal-to-noise; (3) validate in diluted serum to manage fouling while preserving clinical relevance.

HER2 (ERBB2): HER2 overexpression guides therapy in breast cancer, so sensitive, specific, and accessible assays are clinically valuable. Nanofabrication has enabled major jumps in analytical performance:

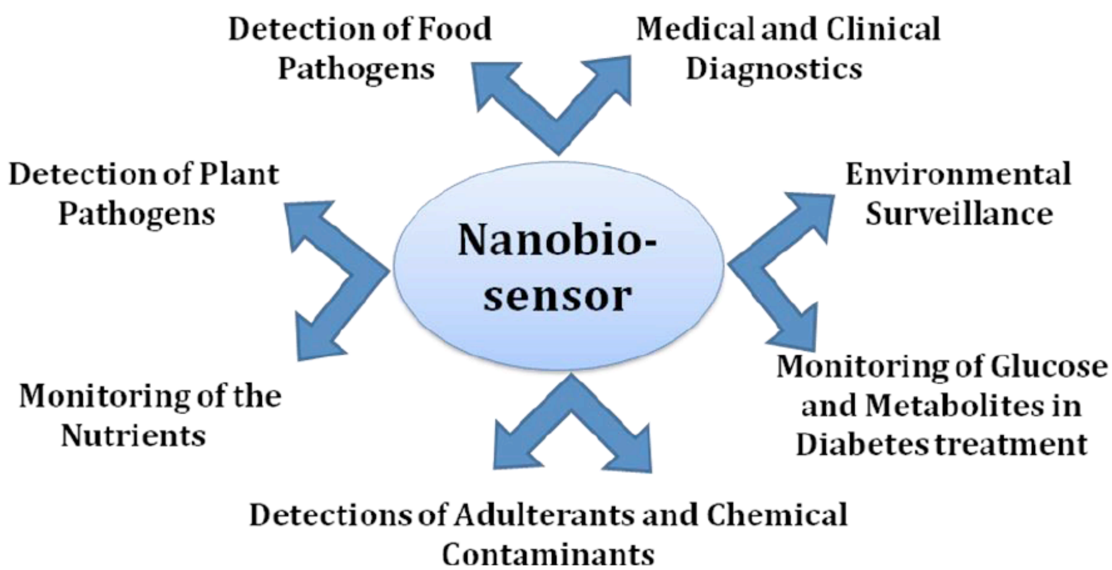

Figure 3: Broad spectrum of potential applications of nanobiosensors.

Electrochemical Aptasensors with Tailor-Made Nano-Hybrids

A 2025 study used ZnOtetrapods coated with a perylene tetracarboxylate (K_4PTC) layer to build a high-surface, conductive interface for HER2 aptamers. The device achieved a linear range from 1 fg mL^{-1} to 10 μg mL^{-1} with an LOD ≈ 0.58 fg mL^{-1}, and worked in spiked serum—illustrating the power of 3D nano-architectures for extreme sensitivity (Rawat, et. al., 2025)

Graphene-based strategies: Reviews highlight that graphene and related 2D materials (often decorated with metal/oxide nanostructures) consistently improve electron transport and probe orientation, enabling label-free or minimally labeled detection of HER2 from liquid biopsy (Kudreyeva et. al., 2025)

Design takeaways: (1) Combine high-mobility nanosemiconductors (graphene, ZnO) with π-rich linkers for aptamer immobilization; (2) apply square-wave voltammetry for dynamic signal; (3) include cross-reactivity tests against near-neighbors (*e.g.*, EGFR family proteins) in serum.

MicroRNAs (miRNAs): miRNAs are short, stable, disease-linked nucleic acids that are excellent early biomarkers but are challenging to quantify at ultra-low abundance.

Label-/enzyme-free electrochemical sensing: Disposable carbon electrodes nanostructured with rGO + AuNPs have detected oncogenic miR-21 in patient serum in a single 30-min step with LOD ≈ 5 fM, demonstrating rapid, clinic-friendly workflows (Zouari et. al., 2020).

Graphene FET (GFET) transducers: GFETs translate surface charge changes from hybridization or CRISPR-mediated cleavage directly into conductance shifts. Recent work pairs exponential HCR or other signal-amplification chemistries with GFETs for fast, ultrasensitive miRNA assays; reviews and new reports emphasize their stability, portability, and potential for wearables/POC. (Huang at. al., 2024; Sun et. al., 2024,2025a)

CRISPR and GFET for amplification-free RNA detection: Integrating CRISPR systems with electrolyte-gated graphene transistors layers molecular and electrical amplification, enabling highly sensitive RNA assays without PCR. This platform is emerging as a compelling route for direct, amplification-free miRNA diagnostics (Sun et. al., 2025b).

Design takeaways: (1) Minimize Debye screening by keeping recognition close to the FET channel and using short probes/aptamers; (2) select amplification (*e.g.*, HCR, catalytic hairpins, CRISPR collateral cleavage) compatible with isothermal, POC operation; (3) rigorously validate specificity against single-nucleotide mismatches.

TRANSLATION CONSIDERATIONS

Across PSA, HER2, and miRNA workflows, three barriers recur: (i) matrix effects (protein fouling, ionic strength) that shift baselines—mitigated with antifouling coatings and dilution strategies; (ii) calibration & cutoffs—LOD is not equal to clinical decision threshold, so calibration with clinical specimens is essential; and (iii) manufacturability—screen-printing and paper/FET platforms help standardize device-to-device variability for regulatory readiness. (Barmpakos et. al., 2025).

INFECTIOUS DISEASE DIAGNOSIS (HIV, COVID-19, TUBERCULOSIS)

Infectious diseases remain a major global health challenge—especially in resource-limited regions where rapid, reliable, and cost-effective diagnostics are crucial. Traditional methods like ELISA, PCR, and culture, while accurate, are often slow, expensive, and require advanced laboratory infrastructure. Nanofabricated biosensors offer transformative advantages—miniaturization, portability, ultra-sensitivity, and rapid turnaround—making them ideal for point-of-care (POC) testing.

HIV Detection

Nanoparticle-enhanced immunoassays have dramatically improved early HIV-1 detection by targeting the p24 capsid antigen. Gold nanoparticle-based biobarcode amplification (BCA) assays achieved detection limits as low as 0.1 pg/mL—100 to 150 times more sensitive than traditional ELISA, which typically detects at 10–15 pg/mL (Tang & Hewlett, 2010). Europium nanoparticle-based immunoassays (ENIA) similarly simplified detection with limits around 0.5 pg/mL (Tang & Hewlett, 2010). These nanomaterial-enhanced platforms can detect HIV infection up to three days before ELISA, significantly aiding early diagnosis in clinical and transfusion settings (Tang & Hewlett, 2010).

COVID-19 Diagnostics

During the COVID-19 pandemic, nanofabricated biosensors, especially graphene field-effect transistors (GFETs) and related platforms, emerged as powerful tools for rapid and ultrasensitive detection of SARS-CoV-2 antigens and antibodies. For example:

- A graphene FET functionalized with spike S1 proteins achieved an antibody detection limit of ~10^{-18} M (~150 antibodies in 100 µL serum) with a diagnosis time under 2 minutes (Lee *et al*., 2021).

- Another GFET using ACE2 immobilization on graphene detected the spike protein at a remarkable detection limit of ~2.94 aM (attomolar), demonstrating high potential for ultra-sensitive screening (Author group, 2023).

- Graphene FET biosensors functionalized with monoclonal antibodies could detect spike protein in human serum in just 100 µs at concentrations as low as 1 fg/mL—equivalent to roughly 8 antigen molecules per µL.

- Additionally, GFETs with graphene oxide channels and Pt/Pd nanoparticle decoration offered rapid and responsive antigen detection, enhancing sensitivity through nanoparticle-mediated signal amplification (Wasfi *et al*., year not specified).

- Moreover, an early GFET COVID-19 sensor could detect spike protein at 1 fg/mL in buffer and 100 fg/mL in clinical transport medium, with LOD of 1.6×10^1 pfu/mL in culture and 2.42×10^2 copies/mL in patient samples—no sample pretreatment required (Seo *et al*., 2020).

These advances underscore the speed, sensitivity, and POC suitability of nanofabricated biosensors during a global health crisis.

Diagnosis of TB

The area of tuberculosis diagnostics has experienced a new hope in nanocomposites biosensors. A chemiresistive biosensor composed of multiwalled carbon nanotube-zinc oxide (MWCNT-ZnO) nanofibers had a linear range of 1.0 pg/mL-6.0 ng/mL of TB lipoarabinomannan (LAM) antigen, detection limit of ~40.54 fg/mL and response time ~102 seconds (Rotake *et al*., 2025). MWCNT-ZnO has a higher surface area and conductivity property that behaves well with antibodies and sensitivity and is thus suited to offer rapid, POC TB testing in high-burden settings.

Overall Impact

Biosensors which have been nanofabricated are an imminent paradigm shift in the diagnostics of infectious diseases. By allowing quick, sensitive and portable identification of pathogens- often at the micron/attomolar level-the technologies fill the gap between clinical suspicion and definitive diagnosis. The sooner and more precise detection of HIV, COVID-19 and TB occurs, the better patient outcomes will be, the less it will spread, and the better a nation will be able to manage it overall.

2. Monitoring of Glucose and Metabolites in Diabetes Treatment

The management of diabetes has changed tremendously with the enhanced instrumentations of glucose and metabolite readings, which informs the patient and the medical personnel in real time with the information on how to improve their treatment regimens. One developmental technological advancement is continuous glucose monitoring (CGM) devices, which help monitor the levels of glucose frequently and, therefore, help patients control their condition with more predictable results than fingerstick tests (Vigersky *et al*., 2017). These devices detect glucose levels during the day and night which will give useful information on changes and patterns that can be used to adjust insulin dosage.

Recent studies emphasise the effects of CGM on a decreasing level of HbA1C and reductions in the number of hypoglycaemic events. In one study, Lin *et al*. (2021) reported that the use of CGM in patients with Type 1 and Type 2 diabetes resulted in a modest but significant decrease in HbA1c without associated increases in the risk of experiencing Hypoglycemia. In addition, CGM has the potential to offer actionable results in glucose variability that plays a key role in long-term diabetes complications (Hirsch *et al*., 2015).

Besides glucose monitoring, metabolites, *e.g*., lactate, ketone, and fatty acids, can be analytically evaluated to provide a more detailed description of the metabolic condition of diabetic individuals. In particular, ketone monitoring plays an important role in the prevention of diabetic ketoacidosis (DKA) which is a life-threatening complication, especially in Type 1 diabetes (Dhatariya *et al*., 2017). This wider concept of metabolic monitoring in the broader sense is also combined with the newer non-invasive ones such as breath analyzers, wearable technology and others, which face research but eventually provide less invasive approaches to measuring the general condition of the metabolism (Moses *et al*., 2023).

The emerging future of the diabetes management will be to integrate multi-parameter monitoring systems, integrating glucose and metabolite data, to assist with more effective personalized treatment schemes based on improved patient outcomes.

Early Diagnosis of Neurodegenerative diseases: Parkinson and Alzheimer

Early diagnosis of neurodegenerative diseases, especially those including Alzheimer and Parkinson is essential to being able to intervene properly and to better the outcome of the patient. Conventional diagnostic practice is based on clinical manifestations that are evident when the diseases are at an advanced state. Yet, research progress is making it possible to diagnose earlier thanks to biomarkers, imaging, and genetics.

In Alzheimer disease (AD), formation of amyloid-beta plaques and tau tangles in the brain is characteristic. It has been recently discovered that CSF biomarkers, including low concentrations of amyloid-beta and higher quantities of tau protein, can identify AD a decade before its initial manifestation of the disease (Oostveen *et al*., 2021). PET imaging has also become a powerful tool to detect the disorder in the asymptomatic stage as it enables the visualization of amyloid plaques and tau tangles (Ossenkoppele *et al*., 2022). What is more, breakthroughs in blood biomarkers, including plasma phosphorylated tau (p-tau), have shown great promise to detecting AD early, which reduces the invasiveness of this process, as well as makes it more widely obtainable (Li *et al*., 2022).

Detection of Parkinson's disease (PD) is more complicated since it is gradual onset. Clinical assessment is still considered the gold standard of diagnosis but imaging is starting to gain prominence such as dopamine transporter (DAT) scans and MRI for early-onset diagnosis. Genetic testing also contributes, since mutations in genes like LRRK2 and SNCA can put someone at risk of PD, before motor symptoms have appeared (Deng *et al*., 2025). The research has revealed that these symptoms such as olfactory dysfunction, sleep disturbances, and voice changes could be important indicators of PD at the prodromal stage through the analysis (Gu *et al*., 2024).

Artificial intelligence (AI) and machine learning are emerging technologies that are transforming early detection of neurodegenerative diseases by using complex data of biomarkers, imaging and clinical assessment to predict the incidence of the disease before the actual symptoms occur (Fanijo *et al*., 2023). The aim is to detect the at-risk subjects at an early stage, so that the disease progression could be slowed and quality of life improved.

Environmental Surveillance: Heavy metal detection (Lead, Cadmium and Mercury)

Heavy metals including lead, cadmium, and mercury that can enter the environment are a concern because they can cause diseases to people and environmental sustainability. Such metals are harmful at low amount and can build up in any ecosystem causing prolonged deleterious effects on human health and animals. The developments in environmental monitoring methods have really enhanced the sensitivity of these methods, their accuracy and the efficiency of gauging these pollutants.

Communities: Lead, cadmium and mercury are often within industrial discharge, agricultural drainage and polluted drinking water. The health hazards of such metals include neurological deformity, renal failure and development problems, especially among children. This has made environmental monitoring very essential to give early warnings and mitigate.

Atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) are conventional approaches to lead detection that are high sensitivity (Javaid *et al*., 2023). However, recent developments have led to the development of mobile devices, *e.g*. field-based electrochemical sensors, that support real-time detection and on-site analysis resulting in more immediate responses to monitoring activities (Ahmed *et al*., 2025). Equally, cadmium and mercury have been characterized by the advanced technologies that have allowed their faster and efficient detection in environmental samples *e.g*. soil, water and air.

Mercury is especially difficult to monitor, owing to its volatile substance nature. Improvements in atomic fluorescence spectroscopy (AFS) and cold vapor atomic absorption spectroscopy (CV-AAS) have been found useful in the detection of mercury levels in environmental samples (Garc aacute -Mesa *et al*., 2021). Also, the emergence of biosensors and nanomaterial-based sensors expands the potential of sensitive detection approaches with limited sample pre-processing, offering a cost-effective solution to large-scale monitoring (Buledi *et al*., 2021).

Also, satellite-based technology and remote sensing has increased large scale monitoring, of areas that traditional monitoring would not be feasible. Such technologies allow sensing the metal contamination in space, which can give a wider coverage of areas vulnerable to such pollution (Lovynska *et al*., 2024).

With environmental pollution due to heavy metals increasing, incorporation of the more efficient detection methods is vital to successful control, prevention, and remediation strategies.

Evaluation of Pesticides and Herbicides in the Soil and Water

A significant part of environmental protection and the health of the population is the monitoring of pesticides and herbicides in water and the soil realm. The use of these chemicals, which have popular applications in agriculture, can be highly dangerous to the well being of the environment and people because they are toxic and take a long time to break down in the environment. The monitoring methods used must be effective to detect, evaluate, and address the level of contamination so that agricultural commodities, water bodies, and wildlife could be safe.

Pesticides and herbicides are intended to help control a collection of pests and weeds, yet they can be adverse to non-target organisms and could impact human life when they dissolve into the water and earth. These chemicals therefore need to be sensitively and accurately detected so that the level of contamination can be evaluated and the environmental regulations enforced. Conventional techniques like gas chromatography (GC) and liquid chromatography (LC) along with mass spectrometry (MS) have been the standard of analysis of pesticide and herbicide in the environmental samples (Yuan *et al*., 2023). The techniques provide high sensitivities and specificities but need special equipment and expertise thus are less suitable in the field.

To help address the need to instigate on-site and rapid detection, there have been innovations of portable and affordable sensors. Another method of detecting the specific pesticides and herbicides in water and soil is the increasing use of immunoassays, including enzyme-linked immosorbent assays (ELISA). Such sensors are versatile, consumable (cost-friendly) and can be used in agricultural settings in routine working environments (Khan *et al*., 2021). Moreover, real-time detection and quantification of the additives at trace level have been promising with electrochemical sensors and biosensors based on the nanomaterial and molecular recognition elements (Mirres *et al*., 2022).

New technologies such as remote sensing and geographic information systems (GIS) are also finding application where they are used to track pesticide and herbicide applications and dispersion within agricultural sceneries. These technologies have the potential to identify zones of high contamination, and make forecasts on contamination patterns which can be used when it comes to decision-making and enforcement action by regulatory bodies (Zhou *et al*., 2021). Besides, these technologies coupled to machine learning have led to more precise and efficient predictive models to monitor pesticide residue over a period of time (Feng *et al*., 2021).

The combination of such enhanced monitoring technologies has greatly enhanced our capacity to monitor pesticide and herbicide contamination within the soil and the water. Such methods will not only benefit regulatory authorities with vital information, but will also ensure that farmers make the transition towards more sustainable farming practices by reducing use of chemicals and eliminating contamination.

Detecting Airborne Pollutants: NOx, SOx and VOCs

Emission of air pollutants especially nitrogen oxides (NOx), sulfur oxides (SOx), and volatile organic compounds (VOCs) are the primary causes of air quality degradation, which has great consequences to the environment and the health of the people. Detection of these pollutants is very important in terms of regulation compliance, air quality observation, and in developing the best mitigation methods to curb their effects. With the recent improvements in the field of sensors and analytical techniques, the detection and monitoring of these atmospheric pollutants has improved a great deal.

The nitrogen oxides (NOx) are made up of nitrogen dioxide (NO_2) and nitric oxide (NO) and are the result of combustion processes like vehicle emissions and industrial activities. These pollutants are important sources of ground level-ozone and particulate matter, which are hazardous to the health of humans and the environment. In conventional detection, specifically the detection of NOx, chemiluminescence spectroscopy and non-dispersive infrared (NDIR) spectroscopy are used, which were effective and having high sensitivity and accuracy of detection (Owen *et al*., 2024). Recent advances have spawned the development of portable electrochemical sensors that makes it possible to do on-site monitoring, invaluable when it comes to gaining real-time monitoring of the air quality in the urban setting, especially in places that have a high level of traffic emissions (Zuidema *et al*., 2021).

SOx (dominantly sulfur dioxide or SO_2), initially due to the burning of fossil fuels in power plant, industrial procedures, and vehicles. Ox pollutants may cause acid rain which in turn may cause havoc to ecosystems, buildings, and human health. conventionally, measurement of SOx has been done through fluorescence and NDIR spectroscopy which give accurate interpolations of SO 2 concentrations (Wang *et al*., 2023). Most recently, photoacoustic spectroscopy is being researched as a potentially better real-time method of monitoring SO 2 with high sensitivity, and little to no interference by other gaseous components (Qi *et al*., 2024).

OCs are a heterogenous family of organic materials which are released by a various set of sources, such as automobile exhaust, industrial processes, and consumer products. The OVCs also form ground-level ozone and smog which is dangerous to the respiratory system. Monitoring of VOCs has been traditionally performed by gas chromatography-mass spectrometry (GC-MS) that offers high sensitivity and precision (Vaye *et al*., 2022). Recent advancements in technology that include metal oxide semiconductor (MOS) sensors and photoionization detectors (PID) are portable, real-time detectable and are ideal in monitoring the environment especially in cities and the rural areas (Wiśniewska *et al*., 2022).

Earlier recent developments in terms of sensor fusion and remotely sensed technologies have enhanced the pollutant detection in air. Satellite- and drone-based remote sensing has brought forth the possibility of monitoring vast geographic coverage at once and has provided data that can aid policymaking and enforcement of pollution-control efforts (Bahadur *et al*., 2023). To further improve predictive potential, machine learning models are combined with real-time data of sensors that provide updated information about the levels of pollutants and their effects in monitoring air quality.

Air quality monitoring improvements will require the continued development of portable, cost-effective, and accurate detection techniques that will help improve air quality monitoring and eliminate the health impact of air pollution.

Microbial Contamination in the Natural Ecosystems

Microbial contamination within the ecosystem is a crucial environmental issue, because microorganisms are vital in aspects of material cycling in the ecosystem, decomposition, biodiversity conservation in the ecosystem. The above-mentioned processes can be disrupted by the introduction of pathogenic or invasive microorganisms into the environment caused by some human activity, and the consequences of such processes turn out to be harmful to the biodiversity of nature, its stability, and even to human health. There are important links between microbes and natural ecosystems including sources, detection and effects. This understanding is important in the conservation and management of natural ecosystems.

Microbial contamination of natural ecosystems is mainly caused by human activities like pollution by industries, farming run offs, and waste water discharges. These may include bacteria, viruses, fungi, and the protozoa and will tend to erode the quality of water, soil health, and the entire ecosystem. Agricultural run off, normally contaminated with fertilizers and pesticides, can result in the expansion of pathogenic microorganisms, including Escherichia coli, and Salmonella in freshwater bodies (Albou *et al*., 2024). Likewise, letting loose untreated sewage into natural water can result in the introduction of pathogenic organisms that will not just expose life forms in the water to such dangers but also humans who may be dependent on this water as a source of drinking and recreational water.

New revolution in molecular biology and genomics has transformed how microbial contamination is spotted and followed. Conventional techniques, including culturing and microscopy are lengthy and sometimes insensitive. Pool sequencing and metagenomic sequencing, in contrast, provide faster and more holistic methodologies of identifying microbial population and identities of specific pathogens spores in the environment (Goncalves *et al*., 2023). The methods allow the identification of both culturable and unculturable microorganisms to enhance the level of detecting contaminants that have never been specified before.

The effect of microbial contamination to natural ecosystems is enormous. In waterways, to take one example, excess growth of potentially harmful microorganisms, including harmful algal blooms (HABs) due to nutrient pollution, can reduce oxygen levels and kill fish, scrambling the food chain (Igwaran et. al., 2024). In the same manner, contamination of soil by disease-causing microorganisms may change microbial composition and soil fertility, which affects agricultural practices negatively and plants are unable to grow. In marine environment, the establishment of non-native pathogens has the potential of causing the extinction of natives and ecosystem services located in their habitat (Delaeter *et al*., 2022).

A very important way of ensuring effective management of microbial contamination in natural ecosystems is by the formulation of effective strategies of prevention and remedies. Microbial contamination can be reduced by the reduction of chemical fertilizers and pesticides utilization, treatment of wastewater prior to its discharge, and enhancing waste management. Moreover, the use of bioremediation processes that involve the deployment of microorganisms to degrade pollutants has been demonstrated to contain polluted soils and waters (Muthukumaran *et al*., 2022).

Conclusively, microbial pollution in the natural ecosystems is a big threat to the biodiversity, human health and ecosystem services. There is a need to conduct further research on the methods of detection, as well as appropriate environment-friendly management of the environment; to ensure that these risks are mitigated and the integrity of the natural systems preserved.

Rapid Detection of Food Pathogens: Salmonella, E.coli and Listeria

Foodborne pathogens including Salmonella, Escherichia coli (E. coli), and Listeria monocytogenes are of great public health concern and are causing foodborne diseases and outbreaks worldwide. Detection of these pathogens in food products is important in order to enforce food safety and avoid health catastrophes of the general population. The use of microbiologically traditional methods, although having high precision, is cumbersome and time-consuming in time consumption, and specialized laboratories are required. Over the past few years, technology has improved the speed and efficiency of detection methods and circumvented the need to send specimens to a laboratory, thus providing prompted solutions concerning food safety.

One of the most common offenders of foodborne illness is Salmonella; this is commonly present in poultry, eggs, and meat products. Conventional culture methods of detection may require days before results will be obtained. Detection times have also become relatively short since modern technology has come up with polymerase chain reaction (PCR), immunoassays and biosensors. Such methods as PCR-based approaches to screening, *e.g.*, are able to determine the presence ofSalmonella in foodstuff in a matter of hours by amplifying the DNA of the pathogen (Ndraha *et al*., 2023). Lateral flow immunoassays and biosensors that rely on the antibodies that target Salmonella antigens are an alternative showing promise due to their speed, portability, and reliability in a laboratory and field environment (Younes *et al*., 2020).

E. coli, specifically O157:H7, is also a big player in food poisoning food borne illness primarily in beef, vegetables and dairy products. The usual effective methods of detection of E. coli have been culturing and biochemical analysis methods that may require as much as five days to give results. But, faster means of test, such as PCR, enzyme-linked immunosorbent assays (ELISA), and surface-enhanced Raman spectroscopy (SERS), have seen significant improvements in the time required to perform the test (Kabiraz *et al*., 2023). Techniques such as PCR-based can be used to detect particular genetic markers of E. coli as little as 6-8 hours. On another front, E. coli detection using ESSS is proving to be highly sensitive in food matrices although there is potential of real-time analysis in food production facilities (Zhu *et al*., 2023).

Listeria monocytogenes is of particular concern in that the bacteria can grow at refrigeration temperatures and cause severe illness, notably to vulnerable populations, including the younger and the elderly. There is a need to control outbreaks by rapidly detecting Listeria in food and some of the methods have been developed to solve the problem. CR and real-time PCR are more usual methods of rapid identification, and they can take a few hours. There have been the adaptation of immunological techniques such as ELISA and lateral flow assays to Listeria antigen in food products. Even further developments of nanomaterial-based biosensors, as well as electrochemical sensors, have demonstrated possible high sensitivity rapid detection being performed on-site (Wang *et al*., 2020).

The implementation of these fast detection methods to food safety regimes has changed the manner in which food borne pathogens are being monitored. The techniques are faster in delivering results and therefore, the contaminated products that are to be identified will take a shorter period and chances of diseases will be minimized. In addition, there is increased use of portable and point-of-care instruments in field testing, which enables the input of food safety professionals to test at the production locations, distribution premises or food service establishments.

In summary, there should be diagnostics of foodborne pathogens, such as Salmonella, E. coli, and Listeria, in the shortest possible time to keep food and protect the health of citizens. As technologies change, molecular techniques, serological applications, and sensor-based applications have become more available to professionals in food safety that not only shorten response times and positively affect contaminated food risks.

Amines and Aldehydes are Food Freshness Indicators that can be Monitored

The food freshness plays one of the most important roles in its safety, nutritional value, and general sensory issues. Food decay results in the formation of by-products, to include amines and aldehydes, as food deteriorates due to chemical change. The compounds are widely employed to demonstrate food freshness and decay, because they rise in proportion to microbial action and enzymatic degradation that take place throughout storage. Observation of these compounds has now become a necessary element of food quality management, as it allows the spoilage to be detected prior to the emergence of the evident signs.

In particular, the biogenic amines putrescine, cadaverine, and histamine may be formed during the microbial decomposition of proteins. These may be present in large amounts in protein-rich foods, such as meat, fish and cheese. Raised degree of biogenic amine is related to the cultivation of spoilage bacteria and is utilized as a sign of loss of food. Hypothetically, the presence of high levels of putrescine and cadaverine in the meat spoilage caused by Escherichia coli and Listeria monocytogenes are known (Li *et al*., 2023). Trace amounts of these amines may be detected using^sc- University of Minnesota- sky Kingston, using chromatography-based techniques, including but not limited to high-performance liquid chromatography (HPLC) or gas chromatography-mass spectrometry (GC-MS) (Shashank *et al*., 2021). They are time consuming and need personnel with skills and they are susceptible to give high sensitivity and specificity.

Most recently, rapid detection tests have been invented to give the result at a quicker rate. Enzyme-linked immunosorbent assays (ELISA) and biosensors that target amine-specific molecules are also becoming popular because they are significantly more sensitive, easier to use, and have the potential of being used on-site (Givanoudi *et al*., 2023). These techniques allow the food processors and retailers to make real-time inspection in foods, freshness, and are able to inspect food quality and safety.

Aldehydes which are another set of compounds connected with food decay can be formed by the oxidation of fats and oils. The common aldehydes *e.g.*, hexanal and 2- hexenal are typical indicators of lipid oxidation which is a key contributor to rancidity in fats and oils. This is more common in the case of perishable products like fish, meat and dairy. Monitored levels of aldehydes can be implemented to evaluate the freshness of these kinds of products as well as the shelf life of these products (Dragoev *et al*., 2024). The conventional techniques involved in detecting the presence of aldehyde are gas chromatography (GC), and headspace solid-phase microextraction (SPME) that can be used to analyze the trace в level of aldehydes within foodstuff (Liao *et al*., 2021). Though they give accurate results, these procedures tend to need specialised equipment and are thus not applicable in a food production environment.

At an attempt to meet the demands of more convenient and less time-consuming testing, scientists created smaller devices that are able to detect the levels of aldehydes even in low concentrations. They are electrochemical sensors, optical sensors, and surface-enhanced Raman spectroscopy (SERS) (Nagpal *et al*., 2023). The benefits of these sensors are that lipid oxidation can be detected on-site in real-time without the need to be analyzed in a laboratory, therefore enabling food producers and customers to estimate freshness of food.

These advanced methods of detecting amines and aldehydes incorporated in the food quality control procedures have transformed the control and monitoring of food freshness. By allowing the effective and fast identification of indicators of spoilage, these methods can help make food safer, manage stocks more efficiently, and limit food waste. The production of easy-to-carry, simple to use sensors provides an exciting opportunity to simultaneously detect food freshness at real-time production-to-sale settings.

Detections of Adulterants and Chemical Contaminants: Melamine and Antibiotics

Contamination and food adulteration are major threats to food security, since they threaten the health of the consumers and the integrity of food. Melamine and antibiotics are two types of common food product contaminants and have serious health effects to the society. Melamine is an industrial chemical that is frequently added to food illegally, even as antibiotics are added to raise animals to maximise growth and prevent disease. Laboratory investigation techniques are needed to effectively detect these adulterants in order to make food safe, and win consumer confidence.

Melamine Detection:

With the example of infant formula in 2008, melamine contamination was thrust into the spotlight of media attention as a result of causing severe health effects, including kidney damage and even death among infants. Melamine in food products: especially dairy, has emerged as a point of concern, since then, among food safety authorities around the world. Melamine can usually be detected by chromatographic methods like high-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS) and have high sensitivity and specificity (Kaloo *et al*., 2024). Yet, these methods take a lot of time, are costly and needed specialized lab apparatus.

Most recent advancements related to rapid detection technologies have been aimed towards portable and low cost technologies that can be utilized on-site. Enzyme linked immunosorbent Assays (ELISA) and lateral flow immunoassays (LFIA) are commonly used to detect melamine in food as they are rapid. These immunoassays-based techniques use antibodies which affiliate to the melamine molecules, and an outcome is obtained within some minutes (Yue *et al*., 2022). Bio- and electrochemical sensing devices with nanomaterials and molecular identifying components are also promising in the detection of melamine at low levels in food products (Wang *et al*., 2022). These probes have the prospects of detection in real time and assistance in place that help to respond faster in food quality management.

There is Detection of Antibiotic Residues

The antibiotics use in animals farming has sparked fears over presence of antibiotic residues in food, particularly meat, milk and eggs. Presence of antibiotic residues in food may facilitate emergence of antibiotic resistant organisms, which are a threat to human health. Hence, to detect the presence of antibiotics in foods, the most common methods are liquid chromatography-tandem mass spectrometry (LC-MS/MS), enzyme-linked immunosorbent assays (ELISA), and microbial inhibition tests (Khatibi *et al*., 2021). LC-MS/MS is the gold standard but is inferior to rapid techniques in terms of sensitivity and is unaffordable to carry out regularly in food production facilities.

In order to meet this demand of faster and more convenient test results, scientists have come up with fast diagnostic means of antibiotic residue confirmation. Lateral flow assays (LFAs) were originally designed as pregnancy tests but they have been adapted to test food residue to antibiotic residue. They are easily operated, inexpensive, and can give results within minutes, which is a quality that would make them well suited to food processing industries and the field (Li *et al*., 2023). A potential solution is also the development of biosensors, both electrochemical and optical, to identify particular antibiotic residues at low levels, which is another promising method to monitor in real-time (Khan *et al*., 2022).

The biosensors, immunoassays and microfluidic device integration have resulted in the so-called lab-on-a-chip systems to detect melamine and antibiotic residue. These devices can conduct high throughput, multiplexed analyses in a short time frame on-site with minimal costs as compared to conventional laboratory techniques (Sridhar *et al*., 2022). Furthermore, the methods are applicable in high throughput screening of food products, thus ensuring tainted or contaminated food products are not sold into the supply chain.

Determination of adulterants and other chemical contaminants (*e.g*., melamine and antibiotics) in food is essential to food safety and the protection of human lives. The development of the rapid detection technologies immunoassays, biosensors, and microfluidic device has also contributed greatly to the real time monitoring of the quality of the foods. Such techniques represent the potential of on-site and cost-effective testing of food products, and the proposed developed methods can give food producers, regulation bodies and consumers the means to avoid adulteration and contamination during the food supply chain.

Shelf-life extension, and smart package sensors

Saving shelf life and improvement of quality foods are critical goals in the present day food business whose consumers keep insisting on safe and fresh foods. Shelf-life extension technologies are used to lengthen the food storage life, whereas smart packaging sensors help to monitor in real-time whether the food goods are kept at optimum conditions during their distribution and consumption worlds. Collectively, these technologies are transforming the food safety and quality management systems offering the advantage of minimizing wastage of food, improved inventory, and consumer confidence.

Urethane Shelf-Life Extension:

One of these processes is called shelf-life extension: it is the technology and methods that aim to lengthen the freshness, quality and even safety of food goods. The common procedures of shelf life extension are modified atmosphere packaging (MAP), vacuum sealing, refrigeration, and preservatives. These procedures are effective because they minimise the elements that enhance speedy deterioration like oxygen, light, temperature and microbial activity.

Modified Atmosphere Packaging (MAP): MAP is used to change gasses (such as, oxygen, carbon dioxide, and nitrogen) inside a bend to reduce the pace of oxidation and microbial growth. As an example, the growth of aerobic bacteria and fungi in fresh produce and meat products can be highly retarded by reducing the amount of oxygen in them (Zdulski *et al*., 2024). The technique is popular within the majority of fresh cut meat, fruit and vegetable industries.

Vacuum Packaging: In this process, air is taken out of a package and sealed up thus hindering oxidation and slower growth of aerobic microorganisms. Vacuum packed is popularly used on meat, cheese, and other perishables (Siddiqui et. al., 2024).

Refrigeration and Freezing: Lowering temperatures is perhaps the best method of slowing the enzymatic and microbial processes that cause spoilage. Although refrigeration can preserve the shelf life of dairy products, fresh produce and prepared meals, freezing is often used with frozen vegetables, meat, and fish.

Natural Preservatives: The new advancement in natural preservatives, including antimicrobial plants (*e.g*. essential oils, chitosan, and vinegar), has received focus as a more sustainable and health-friendly alternative to synthetic additives (Novais *et al*., 2022). They can use these preservatives to ensure that they manage microbial growth and have an extended shelf life without affecting food safety or its flavor.

Smart Packaging Sensor

Smart packaging or even intelligent packaging, also involves the utilization of sensors and indicators which are able to produce real time knowledge of the status of food products. These detectors observe many things that make the food quality, *e.g*., temperature, humidity, gas composition, and microbial activity. Placeable smart sensors in packaging systems have birthed active and passive packaging technologies that support better product quality control and guaranteed safety.

Temperature and Humidity Sensors: The temperature is one of the major issues that determine the shelf life particularly when it comes to perishable foodstuffs such as dairy, meats and seafoods. Smart packaging solutions have taken it a notch higher to now incorporate temperature and humidity sensors, which check the storage conditions within the supply chain of the product. These sensors deal with real-time information on the temperature history of the product, and so the producers and the consumers have the option to check whether the goods inside have been maintained at the right temperature (Cheng *et al*., 2022).

Gas Sensors (Oxygen, Carbon Dioxide, Ethylene): We have previously noted that MAP is based on changes to the composition of the atmosphere within the package in order to extend shelf-life. In order to measure the efficacy of MAP, it is possible to introduce the gas sensors into the smart packaging to see the oxygen, carbon dioxide, and ethylene amounts, which are the major signs of food ripening, microbiological growth, and spoilage. To illustrate, the high ethylene production may point out that fruits are ripening too fast, which means that there may be a necessity to change storage conditions (Shaalan *et al*., 2022).

pHand Volatile Organic Compound (VOC) Sensors: pH meter can change over time as the food product goes bad due to microbial growth or other changes. By placing a pH sensor in packaging, real-time monitoring of how acidic or alkaline the food is can help detect spoilage. In the same manner, VOC sensors would be able to detect the emission of particular gases during spoilage, which would be an early warning system to the producers and consumers (Lin *et al*., 2023).

RFID and NFC (Near Field Communication): Radio Frequency Identification (RFID) and NFC tags are also being added to the packaging to track and monitor packaging in a more superior way. They can remember all the information about this product: the history of temperature in which the product was stored, and its expiration date, which can be read by a consumer to ensure the quality and safety of this product in real-time (Mostaccio *et al*., 2023).

The Path Forward and Advantages:

The future of shelf-life extension and smart packaging rests with incorporating more advanced technologies, including nanotechnology, artificial intelligence (AI) and the Internet of Things (IoT). Nanomaterials are being created in order to be used in packaging films as barrier to enhance barrier properties and oxidation prevention activity as well as antimicrobial activity. In the meantime, AI and IoT partnership will provide even more advanced predictive modeling of shelf life so food manufacturers will be able to real-time adjust their storage and distribution systems depending on the sensor data.

The advantages of smart packaging and shelf-life extension technologies are manifold:

1. Food waste reduction: These technologies can considerably reduce food waste during transportation and in household shelves because they extended the shelf life and allow visualizing the food in real-time.

2. Better Food Safety: Constant monitoring is able to stop contamination and products consumed before they can even get to dangerous states.

3. Consumer Confidence: Data-driven packaging bestows possibilities to offer transparency to consumers and give them assurance about freshness of food as well as safety of food products in the market.

4. Sustainability: Optimal packaging systems will help to reduce spoilage and waste of food and this contributes towards the realization of sustainability goals as well as reduce environmental effect of any food production process.

The ability to extend the shelf life and use smart packaging sensors is the new transformation in food industry because of the growth of food safety and sustainability acceptance and related quality improvement. Such innovations are useful to producers, retailers, and consumers in ensuring better management of food products, minimization of food waste, and food security in general. With advancing technology, the future of food preservation and packaging is more optimistic with new opportunities when it comes to developing smart, Safe and efficiency in food systems.

Detection of Plant Pathogens: Fungal, Bacterial and Viral Plant Infections in Agricultural Practices

Plant pathogen detection is a major agricultural management process since plant diseases caused by fungi, bacteria, viral infections have the potential to damage crop quality and yield and also food security. Early and precise detection enables effective management of the disease and also, reduces the chemical interventions hence enhancing sustainable agriculture. The increased availability of advanced technologies of detection has enhanced speed, sensitivity and accuracy of the identification of these pathogens and this enables farmers and other professionals in the agricultural field to better cope with outbreaks.

Fungal Pathogens:

The fungal infections are one of the most common and harmful diseases of the plants that include rust, blight, and mildew. Fungal pathogens are able to infect most plant organs, including roots, as well as survive in a range of environmental settings. Early identification of fungal pathogens is needed to limit the development of the infections and limit their effect on the crop productivity.

Olden ways of determining fungal pathogens: Fungal pathogens have in the past been diagnosed by culture based methods, in which the samples of diseased plants are cultured in selective media. These methods however are time consuming, and usually highly skilled interpretation is required.

Molecular Detection: Polymerase chain reaction (PCR) and real-time PCR has transformed fungal pathogen detection by being able to identify specific DNA that is attributed to certain fungal species. The techniques are very sensitive and they can regulate fungal infections at early stages even before symptoms can be seen (Ali *et al*., 2020). The quantitative polymerase chain reaction (qPCR) can be especially beneficial as a method of tracking fungal populations on crops in order to allow farmers to take preventative measures against infections.

Biosensors and Imaging Techniques: Advancement in biosensor technology has made it possible to make portable sensors that are able to detect fungal pathogens in a real time scenario. Optical methods are making use of optical sensing including fluorescence-based technology and surface-enhanced raman spectroscopy (SERS) to detect fungal infections based on the changes in metabolism or expression of fungal structures (Dyussembayev *et al*., 2021). An emerging technology is hyperspectral imaging that reflects light off the plant to detect fungal infection early on by using light before the naked eye can see it.

Bacterial Pathogens:

Bacterial plant infections may give rise to plant diseases like bacterial wilt, soft rot and leaf spot. These pathogens are usually transmitted by polluted water, soil, and seeds and thus can easily destroy crops before they are detected and chemicals used to contain the attack.

Conventional Processes: Bacterial pathogens have conventionally been identified by growing the bacteria by use of culturing method through which bacteria colonies are observed on an agar media. This technique is a common practice in most laboratory set ups but it is time consuming and preparation is high.

Molecular Diagnostics: Traditionally, real time PCR and lateral flow immunoassays (LFIA) are widely used in order to identify the presence of bacterial pathogens. CR-based technologies are highly specific and sensitive in terms of bacterial DNA detection, and LFIA devices significantly simplify the results by means of rapid on-site analysis by farmers (Gerace *et al*., 2022). Such immunoassays are antibody-based assays used to sense bacterial antigens, and can be employed in field or laboratory testing.

Nanotechnology and Biosensors: Bacterial pathogen detecting nanomaterials-based sensors including those of gold nanoparticles and carbon nanotubes are being investigated. These sensors increase sensitivity of conventional methods and they can be monitored in real time. *e.g*., magnetic nanoparticles with PCR technology has been employed to enrich and multiply target bacteria DNA, and would be highly valid in differentiating and discovering low-level infections (Singh *et al*., 2023).

Viral Pathogens:

Plant viral diseases such as tomato spotted wilt virus (TSWV) and tobacco mosaic virus (TMV) are very difficult to control as traditional mechanical methods of airborne plant viruses removal may not likely to work. Such pathogens may severely reduce yields and are commonly spread by a vector, such as an insect.

Conventional Detection Techniques:EM May 2021 Viral pathogens were conventionally recognized by serological techniques including enzyme-linked immunosorbent bid (ELISA)that identified antibodies against the virus. Although ELISA is viable, it involves trained human resources and the utilization of laboratories therefore making it hard to be applied in the field.

Molecular Prosolete: PCR and reverse-transcription PCR (RT-PCR) has come out as the means to establish the pathogen with viruses. RT-PCR DNA amplification is also highly valuable when screenings are performed to detect plant viruses with an RNA genome. Such approaches are extremely sensitive and will demonstrate any virus in plants that show no symptoms (Zhang *et al*., 2025). In addition to this, the introduction of quantitative PCR (qPCR) has enabled them to receive quantitative measurements of viral loads aiding in the monitoring and management of the disease.

Biosensors for Viral Detection: There has been a recent development of the use of biosensors that can detect viral pathogens within a short period of time and at any location. They are those based on the nanoinfrared effect and nanobiosensors (Chaudhary *et al*., 2021). An example is a biosensor with aptamers (small DNA or RNA molecules) that specifically bind the viral particle that have shown the ability to detect such viruses with high specificity.

SA Integrated Detection Systems

Combination of various detection techniques has boosted the level of overall accuracy and the speed with respect to identification of pathogens. There are the advances of smart sensing technologies like Internet of Things (IoT)-enabled sensors and remote sensing which enable farmers to detect the crop health in real-time and outbreak pathogens in early times. Systems based on the Internet of things (IoT) that combines environmental sensor data (*e.g*., humidity and temperature) with pathogen detection devices can provide insight on real-time crop status and operate proactive mitigation of plant disease (Nagasubramanian *et al*., 2021).

Identification of fungal, bacterial, and viral plant pathogens is of utmost importance across disease management and sustainability in agricultural production. Through advances in molecular diagnostics, biosensors, and remote sensing, the capacity to detect pathogens at early stages has been enhanced and this is oftentimes when the symptoms have not been manifested. Not only do these technologies enable the detection to be more accurate and timely, but also decrease the use of chemical pesticides, aiding more sustainable and environmental friendly farming. With the ongoing development of research, the adaptation of these detection systems in precision agriculture will transform plant disease management, lower crop losses, and increase food security worldwide.

Nanosensor Related soil Nutrient and pH Monitoring

Nutrient levels and pH of the soil are important aspects of the soil of a given agricultural land that determines the growth of the plants as well as produce quality of the agricultural produce. Effective tracking of soil nutriment and ph is very essential in optimization of the fertilization process, environmental sustainability, in addition to boosting crop output. Conventionally, testing of soil in terms of nutrient and pH analysis has been a lab component that is time consuming and costly on equipment. The new developments of nanosensors have transformed the approach of soil monitoring because of their capacity to monitor soil continuously in real time, and at the site and at a lesser cost. This review examines the advancement and use of nano sensors to monitor nutrients and pH in soil, extolling its advantages and drawbacks and future opportunities.

Monitoring of the Nutrients in the Soil by use of Nanosensors

The plants need nutrients in the soil nitrogen, phosphorus, potassium, calcium and magnesium. The various nutrients are subject to imbalance which can trigger poor crop production, nutrient losses though leaching as well as pollution of the environment. Proper and real-time assessment of the nutrients of soil is important in regulating the use of fertilizer, over-fertilization, and enhancing nutrient efficiencies.

Nano Sensors of Nitrogen (N): Nitrogen is one of the key nutrients in agriculture and to maintain the level of nitrogen, it is necessary to monitor the amount of the nutrient and avoid overuse of fertilisers and pollution effects. Nanosensors used in detecting nitrogen usually identify alterations in the chemical composition of the soil or the uptake of the plant. As an example, carbon nanotube (CNT) based nanosensors or metal oxide nanoparticle (MO-NP) nanosensors may be used to sense nitrate and ammonium ions in the soil. They are usually functional by relying on the effect that the interaction of the nitrogen compounds can alter the conductivity or the optical properties of the sensor materials (Tyagi *et al*., 2022).

Nanosensors on Phosphorus (P): The other element that is important to plant growth is phosphorus level in the soil. Nanosensors used to detect phosphorus are usually quantum dots or nanoparticles used to bind with phosphates with a lot of sensitivity and selectivity. Such sensors may facilitated onsite and real time phosphorus measurement which can allow farmers adjust fertilization to reduce phosphorus run-off hence preventing its impact on the environment (Parameswari *et al*., 2024).

Nanosensors of Potassium (K) and other Nutrients: Potassium, calcium, and magnesium, similar to nitrogen and phosphorous are being developed with nanosensors. These devices are generally based on the ion selective sensor (ISE) and nanomaterials whose electrical, optical, and mechanical characteristics can be altered when they come into contact with certain ions. Such examples are gold-nanoparticle (AuNP) and carbon nanoparticle-based materials, wherein the detection of potassium in soil has been made possible through changes in their surface plasmon resonance (SPR) or fluorescence (Bala *et al*., 2025).

Nanosensor Soil pH Monitoring

Soil pH is most important, even in nutrient availability, microbial activity and plant growth. Farmers should ensure good pH levels in order to get maximum yields in their crops. Conventional methods of pH measurements may be costly and are usually limited by sample processing requirements and collection. Nanosensors provide an attractive alternative to continuous, on-going, in-situ pH measurement in soil.

pH-Sensitive Nanosensors: Nanosensors Detection of pH change in soil typically entails use of pH-sensitive nano particles or polymers that change in color or conductivity under slight changes to acid/alkaline level. As another example, we could mention pH-responsive organic-inorganic hybrid nanoparticles that could alter their color in case of changes in pH conditions and thus could serve as a visual source of information about the pH of the soil (Nadporozhskaya *et al*., 2022).

Optical Nanosensors: Optical nanosensors such as nanoparticle-based fluorescent nanoparticles or quantum dots are common in soil pH monitoring. These sensors operate by gauging emission/absorption spectra of the nanoparticle that varies depending on the pH change in the surrounding environment. With these optical sensors, it is possible to create portable devices that monitor the pH of soil in real-time and deliver constant information on changes in the soil pH (El-Chaghaby, *et al*., 2023).

Electrochemical Nanosensors: Electrochemical nanosensors and include nanoelectrode arrays as well as electrochemical field-effect transistors (FETs) have been utilized to detect soil pH. These sensors measure voltage/current changes that experience with the surface charge difference of the nanomaterials upon exposure to the pH of the soil. The sensors also provide high sensitivity, portability and possibility of having them integrated into IoT-based agricultural systems to monitor them in real-time (Kundu *et al*., 2022). The Benefits of using Nanosensors in soil monitoring is shown in Table **4**.

Challenges and Future Directions for Soil Monitoring:

Even though nanosensors hold important benefits in terms of soil monitoring, a number of issues still need to be addressed before they can become widely used:

1.Durability in Harsh Soil Conditions: Nanosensors should be durable in the harsh soil environment, which are marked by varying degrees of soil moisture levels, temperature up and down and the salts or any organic matter that it may contain. Work on the durability and stability of nanosensors in the real world environment is underway (Mahajan *et al*., 2024).

2.Calibration and Standardization: nanosensors also have to be carefully standardized according to the soil type and atmospheric conditions to work efficiently. Constant standardisation of the designs and procedures of nanosensors applied in the soil testing

Table 4: Nanosensors Benefits in Soil Monitoring

S.No.	Parameter	Benefits
1.	Real-Time Monitoring	Nanosensors will enable real time monitoring of soil nutrients and pH levels so that farmers can make informed decisions relating to fertilization and irrigation methodologies.
2.	Detection portability, and on-site	Nanosensors are often small, and easily deployed in the field, eliminating the need to travel to (or ship to) a laboratory in order to conduct a test, and enabling farmers to test their soils immediately on-site.
3.	Higher Sensitivity and Selectivity	Nanosensors are very sensitive to minute changes in the level of nutrients, pH and will be able to indicate when nutrient levels become imbalanced or when the pH of the soil changes, before the crops are adversely affected.
4.	Cost-Effectiveness	As new methods of fabricating nanomaterials emerge, nanosensors can be more readily implemented in price sensitive precision agriculture settings with cost savings over other methods of soil testing.
5.	Environment Friendly	Nanosensors are always non-toxic, biodegradable and do not have much impact on the environment as compared to the traditional methods of chemically testing the soil.

should be done to provide similarity and dependability between different applications.

3.Interconnecting with IoT Systems: As useful as nanosensors can be they will be even better once interconnected with larger Internet of Things (IoT)-based agricultural systems. The integration is possible with the mean to offer real-time data exchange, autonomous processing, and precision agriculture implementations (Mansoor *et al*., 2025).

Nanosensors will be an innovative technology in the agricultural field of monitoring of soils nutrients, dye contents and soil pH. They could help to optimize the use of fertilizants, increase their production, and reduce the effect on the environment because they allow real-time in-situ analysis of the soil condition (Parameswari *et al*., 2024; Saha *et al*., 2021). Despite the limitations of its potential application expressed in terms of durability, calibration and integration with the bigger agricultural systems there is a great promise that nanosensors will facilitate a breakthrough in the precision farming and would help raise the standards of more environment-friendly agricultural practices.

Accurate farming and regulated irrigation has transformed contemporary farming into making maximum use of resources, maximum crop productivity, and minimum effect on the environment. Among the main technologies to raise this revolution are the use of biosensors which give real time, accurate, and reliable information about the monitoring of various parameters in agriculture. In precision farming and water irrigation, biosensors offer great benefits since they can be used to make accurate estimates on soil, plant growth, and water usage to make sound decisions and provide proper management of resources. This review examines the use of biosensors in precision farming and controlled irrigation in terms of the opportunities and challenges associated with the implementation as well as future directions with regards to adoption.

Biosensors in Next-Gen Farming:

Precision farming refers to the practice of applying the latest technologies to monitor and control the growth process as well as the soil health and environmental conditions with high precision. Biosensors lead the pack in this technology, as farmers can be able to access the most vital data that can facilitate the streamlining of the farming practice.

Soil Health Monitoring: The health of the soil can also be monitored using biosensors in terms of moisture, temperature, pH, and nutrient content which plant health depends on. The detection of soil moisture as well as concentration levels of nutrients is usually done through electrochemical sensors and optical biosensors. As an example, enzymatic biosensors can be used to quantify the amount of nitrogen, phosphorus and potassium present in the ground because of the enzymes that help in nutrient cycles. These sensors assist in ensuring the farmers utilize fertilizers and amendments only when they are necessary and eliminates wastage and run off into the environment (Anchondo *et al*., 2025).

Monitoring Plant Health: Biosensors are also utilized to observe the physiological condition of crops. Plant stress can also be sensed via chlorophyll fluorescence sensors and lower-frequency sensors as a proxy measurement of plant photosynthesis and the level of water stress. Biosensors with optical and electrochemical characteristics have also been used to identify plant disease and infestations through the detection of pathogen presence or its metabolic wastes (Ali *et al*., 2021). Some of the issues could be caught before they become a major problem and thus solutions could be applied selectively without overuse or misuse of pesticides.

Pest and Disease Detection: Biosensors have also been used to detect particular pathogens like fungi, bacteria and viruses at a stage where picture-based or pre-image detection is not possible. Bio-sensors are sensitive and quick detection methods of the pathogens in plants, which could then be managed earlier to prevent a massive loss of crops (Kumar *et al*., 2024). As an example, SERS and lateral flow based immunoassays (LFAs) are being developed to detect pathogens on-site.

Biosensors you can use in Controlled Irrigation:

Water is an important agricultural resource and regulated irrigation systems are vital in disseminating an appropriate supply of appropriate water to the crops at an appropriate time. The use of biosensors is already being utilized in enhancing the efficiency of irrigation system since it gives accurate information relating to soil moisture, crop water condition and environmental factors, in real time.

Soil Moisture Sensors: This is very important parameter in a controlled irrigation, since moisture directly regulates water consumption and crop development. Soil moisture biosensors involve soil moisture level measurement soils that have either capacitive, resistive, or dielectric sensors. Monitoring moisture by analyzing the change in the enzymatic activity of the soil under the effect of water stress is also observed using enzyme-based biosensors (Yin *et al*., 2021). These sensors maintain real-time information to an irrigation system and the system will adjust irrigations that will help eliminate over-irrigation and under-irrigation.

Plant Water Stress Sensors: Precision irrigation is also highly dependent on biosensors that measure the stress (or lack thereof) of plants due to irrigation. Stomatal conductance probes and leaf water potential probes are able to take measurements of how much water a plant is currently losing through transpiration, an index of water stress. These biosensors can assist farmers to come up with the best irrigation times and to not waste water. The electrochemical sensor and the optical sensor can provide better, more accurate, and finer control of irrigation by taking measurements of the water status of plants (Zhou *et al*., 2021).

Weather and Environmental Monitoring: Environmental monitoring which includes the temperature, humidity and solar radiation have a much bearing to the needs of irrigation. Biosensors that are integrated with environmental sensors can measure such variables and give predictive values to schedule irrigation (Table **5**). Microbial sensors to monitor soil microbial communities that affect water retention and nutrient cycling, further increasing the ability to control irrigation, are also being developed (Mansoor *et al*., 2025).

Challenges and Future Directions for Agriculture and Irrigation Systems:

Although biosensors have a lot of advantages, there are a few issues that have to be solved before full integration and implementation into precision agriculture and irrigation systems.

1. Durability and Reliability: The biosensors must be reliable to be transported in harsh environmental factors, like extreme temperatures, water, and salinity to the soil. It is important to design durable and consistent sensors to make them usable in the agricultural fields.

2. Data Integration and Management: It is necessary to combine the data produced by the biosensors with other elements of the wider agricultural management systems, such as IoT platform or cloud tools, to make relevant decisions in real-time. The best way of developing user-friendly programming to the farmers on how to interpret the sensor data sensibly is yet to be solved.

3. Cost and Accessibility: Although the price of biosensors is falling, they remain too expensive to small-scale farmers. It is critical to making these technologies both affordable and accessible to all farmers, especially those in developing nations, in order to realize global adoption.

4. Calibration and Standardization: calibrating biosensors to provide correct values and to be repeatable should be made according to the different types of soils, crops or environmental conditions. The uniformity of biosensor procedures and calibration procedures is important in making such terms thoroughly utilised.

5. Integration with Other Technologies: Integration of biosensors with other technologies, *e.g*. drones and remote sensing, as well as with AI-assisted data analytics, will help achieve more comprehensive monitoring. The future of precision farming will be the bundle of several technologies into the system making the farms smart and optimal on all levels of farm management.

Biosensors hold the promise of real transformation in precision farming and controlled irrigation and a potential path to more sustainable, efficient, and profitable agricultural production. Biosensors can offer

Table 5: Benefits of Biosensors in Precision agriculture and Irrigation

S. No.	Parameters	Benefits
1.	Resource Optimization	Biosensors can help farmers optimize resources by giving real-time information on the condition of the soil, plant health, and water used so they can make more precise decisions and minimize waste.
2.	Cost Minimization	Controlled irrigation and precision farming enabled by biosensors can be highly cost effective by minimizing costs across water, fertilizers, and pesticides and increasing farm profitability.
3.	Environmental sustainability	Correct soil moisture and nutrient monitoring and plant health conditions will reduce environmental impacts like nutrient leaching and excessive irrigations and pesticide use, thereby contributing to environmentally more sustainable agricultural measures.
4.	Identification of plant health states in their early stages	Biosensors have the capacity to identify changes that affect the health and wellbeing of crops before it is noticeable through physical manifestations, allowing early treatment of the problem and decreasing crop losses as a result of pests, diseases, or water shortage.
5.	Automation and Precision	Biosensors could be installed into automated irrigation systems where the exact measure of irrigation could be controlled through automated systems to minimize human error, and provide crops with the ideal amount of water as it depends on the current data.

real-time soil health, plant water status, and environmental conditions data so that the farmers could use the resources with the maximum efficiency, reducing costs and the environmental load. Although some difficulties, which center on such things as durability, data integration, and cost, persist, future agricultural systems promise to includeations in the sensor technology and their integration into more complete agricultural systems.

ISSUES AND PROJECTION OF THE FUTURE

Nanofabricated materials are dramatically transforming nanobiosensors, with the biosensors having the potential of revolutionizing such areas as healthcare, environmental monitoring, and food safety. These sensors provide accuracy and delicate sensitivity never been imagined. Nevertheless, even with these potentialities, manufacturing nanobiosensors to be practical, affordable and widely available remains a number of challenges to be surmounted.

ISSUES OF NANO-FABRICATED MATERIALS AS NANOBIOSENSORS

1. Provided Fabrication Complexity and Scalability

It is just like working on a nanobiosensor by having the patience of creating the best work of art at the tiniest of all scales. Although nanofabrication techniques can manufacture sensors with great accuracy, they are time consuming, costly and not easily scalable. This makes it hard to manufacture high quality serous sensors in bulk without increumenting expenditure. It is like trying to manufacture made-on-demand jewelry- it is time consuming and quite expensive.

2. Integration and Compatibility of Materials

Nano materials in such sensors may not necessarily g*et al*ong with biological systems. Toxicity or instability may be generated when sensors come in contact with the living tissue or biological fluid. Also, over time, the sensors may get clogged or fouled with proteins in the body, preventing them to work as well. Just think of a well-tuned machine being out of doors, where water or dust can readily spoil it. This is a key challenge to medical applications as reliability over long-term is a critical factor.

3. Signal Transduction and Sensitivity

The materials used in nanobiosensors are very sensitive to interaction at molecular level but converting such measurements to an actionable signal (*e.g.* a digital readout or an alert) remains a problem. It is like having a high-tech sensor to appreciate a change but it can not really communicate to you what exactly is happening. Enhancing this capability of neurologic clarity is important in making them a reliable practical help.

4. Standardization, and Matters of Regulation

There is no unified standard to make and test nanobiosensors, so they may work very differently. Additionally, they are constructed using fine particles and new materials, so far, it has been difficult to determine their safety and regulatory agencies are also lagging behind in these issues. It is like using a new form of tech gadget without any user manuals or instructions- a great uncertainty.

PROSPECTS OF NANOFABRICATED MATERIALS AS NANOBIOSENSORS

The trend of nanobiosensors is positive despite the challenges facing it. The following are the ways in which things can be improved:

1. Awards in Fabrication Methods

New fabrication processes are also developing that will hopefully make fabrication of nanobiosensors easier and cheaper on a larger scale. In particular, nanoimprint lithography, as well as roll-to-roll processing techniques, are expected to allow the more cost effective production of such sensors in large quantities. Such methods will reduce prices and make these sensors more affordable to more people, similar to what happened with smartphones when they started being affordable to most people when theászÖCz manufacturing technology improved.

2. Artificial Intelligence (AI)

Nanobiosensors can be considerably optimized with the help of IA. By implementing AI, such sensors would be capable of not only detecting changes that are biological in nature but also analyzing the changes in real-time, providing smarter and more responsive systems. It is like having a personal assistant that serves as a hawk to issue an alarm and even process the data and help interpret it which then makes diagnostics quick and accurate.

3. The evolution of Smart Biosensors

It is possible to envisage that a future where sensors are no longer only detecting problems, but taking action in response to them. Such intelligent sensors could activate automatic therapy, such as by dispensing medicines or moving a machine, in response to the data collected. An example would be a sensor that measures a sugar rise in an insulin-dependent patient to automatically inject the insulin into the patient. Such marriage of sensing and action will lead to a further personalized and efficient healthcare.

4. Green Nanotechnology

There is some issue with the environmental effect of nanomaterial production. But sustainable practices are in the future. Plant-based materials or bacteria used in the process of nanobiosensors could help in minimizing the environs impact. It can be compared to switching to disposable plastic with eco-friendly substitutes and making the whole process not only more sustainable but more secure to the planet.

5. Newer Materials to Improve Performance

Researchers are continuously finding new nanomaterials which could make such sensors superior. *E.g.*, stronger and more effective, new materials, such as graphene (a high-strength, high-conductance material) and quantum dots (tiny particles that emit light when stimulated) can bring prospective advancements in sensitivity, speed, and flexibility. Such materials can be utilized to access novel routes of detecting low-frequency biomarkers or even diagnosis of diseases before the manifestation of symptoms.

CONCLUSION

The creation of nanoscale structures using nanotechnology and nanofabricated materials has led to biosensing devices that are more sensitive, particular, and versatile than ever before. A wide variety of nanomaterials with improved biosensor performance have been created by both bottom-up and top-down nanofabrication methods. These include graphene derivatives, thin films, nanowires, nanotubes, and nanoparticles. These developments have catapulted nanobiosensors into the vanguard of diagnostics in fields as diverse as infectious disease detection, food safety, environmental monitoring, and medicine. An example of this is the remarkable performance of graphene-based biosensors and nanostructured interfaces in detecting viral antigens, cancer biomarkers, and other therapeutically relevant targets with extremely low detection limits and fast response times. By allowing for real-time, accurate, and minimally invasive diagnostics, the incorporation of nanomaterials into portable, point-of-care devices is revolutionizing healthcare. As an example of how nanobiosensors help with illness management, consider the role they play in CGM for diabetics. Their practicality and economic feasibility are being further enhanced by continuous study and invention, in spite of obstacles including device repeatability, matrix effects, and large-scale manufacturing. In conclusion, nanofabricated biosensors are a game-changing technical development that could have far-reaching effects on the diagnosis, treatment, and monitoring of diseases in a variety of settings, leading to better health outcomes and overall human well-being.

CONFLICTS OF INTEREST

The author declared no conflicts of interest.

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