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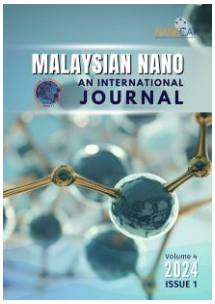

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Recent Advances in Biological Nanodevices and Biosensors: Insights into Applications and Technological Innovations

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Abstract

This paper explores recent advances in the detection of viruses and metals, focusing on how biosensors are revolutionizing environmental management and healthcare. Biosensors have transformed fields such as medical diagnostics by enabling the detection of biological targets at low concentrations. Specifically, graphene field-effect transistor (FET)-based immunosensors have emerged as powerful tools for swiftly and accurately identifying biological targets, opening new avenues in these areas. Furthermore, improvements in metal detection have enabled the monitoring of electrical activity in non-excitable cells, advancing research into cancer bioelectricity and its therapeutic applications. These advancements demonstrate how nanotechnology can innovate approaches in healthcare, offering more sensitive, adaptable, and efficient methods. Additionally, progress in cellular electrophysiology holds promise for enhancing treatments in neurology, cardiology, and regenerative medicine. These advancements can lead to better patient outcomes and expedite the development of bioengineered tissues and organs with integrated electrical properties. This paper explores these groundbreaking applications of biosensors in environmental and medical sciences, highlighting their transformative potential and future directions.

Keywords: Biosensors, nanodevices, biological applications, technological innovations

1. Introduction

Biosensors and nanodevices hold the key to revolutionizing environmental and biological monitoring. By combining biological components with nanoscale materials, these sensors have exceptional sensitivity and specificity in detecting a wide range of analytes. The large surface area and unique quantum characteristics of nanomaterials greatly enhance biosensor performance and enable in situ and real-time biological process monitoring. Research and development efforts are presently in progress to address significant problems and expand the capabilities of these sensors. This may lead to innovative methods for managing the environment and providing healthcare. These cutting-edge technologies have applications in many different industries, including environmental monitoring, medical diagnostics, and food safety. They have a significant promise for improving pollution control, quality assurance, and illness detection.

1.1 Classification of biosensor based on nanomaterials

Graphene in biosensors: Considering its distinctive qualities which includes high conductivity, low resistivity, and a large surface-to-volume ratio, graphene in particular has emerged as a possible solution. Biosensors based on graphene (GOBs) have demonstrated remarkable sensitivity and reaction times, which renders them appropriate for usage such as the detection of viruses, such as COVID-19 and Zika, and cancer cells. Techniques for synthesizing graphene include chemical vapor deposition and liquid phase exfoliation. Recent research has demonstrated graphene FET-based immunosensors for rapid, real-time detection of biological targets at extremely low concentrations, highlighting their potential in medical diagnostics and environmental monitoring. [1]

Gold nanoparticles in biosensors: Considering their special colorimetric characteristics, which cause them to aggregate in the presence of analytes and shift from red to blue, gold nanoparticles (GNPs) are very useful in biosensing. These nanoparticles, which have a diameter of 1 to 100 nm, have a high surface-to-volume ratio and speed up electron transit. Optical, electrochemical, and piezoelectric biosensors are among those that employ GNPs, which exploit their surface plasmon resonance (SPR) to amplify signals. Notably, GNPs have been used to attain high detection accuracy in protein biomarker microcantilever-based biosensors. In addition, they are employed in colorimetric assays that have a remarkable sensitivity in identifying allergens and viral antigens like SARS-CoV-2. Additionally, real-time detection of the hepatitis B surface antigen with low detection limits has been established via hybrid biosensors that combine GNPs with graphene. [1]

CNTs in biosensors: Carbon nanotubes (CNTs) are highly valued for their mechanical, electrical, electrocatalytic, and thermal properties, making them indispensable in biosensor

development. Single-walled CNTs (SWCNTs) typically range from 1 to 2 nm in diameter, while multi-walled CNTs (MWCNTs) can be up to 100 nm in diameter. Double-walled CNTs (DWCNTs) generally exhibit fewer defects compared to MWCNTs. In electrochemical biosensors, CNTs significantly enhance redox activity and sensitivity, especially when combined with materials like polyaniline (PANI). For instance, CNT-PANI nanohybrids achieve a low detection limit of 0.33 femtomolar for Mycobacterium tuberculosis. CNTs are also integral to wearable biosensors, such as gloves coated with CNT/Ag/AgCl, enabling sensitive detection of lactase in sweat. Moreover, in microneedle array (MNA) biosensors for non-invasive monitoring of thermal injuries, CNTs provide high sensitivity with minimal discomfort during skin penetration. [1].

QD-based biosensors: Quantum dots (QDs) are fluorescent semiconductor nanocrystals that are less than 10 nm in size. Their excellent optical and electrical capabilities make them valuable in the field of biosensing. Carbon quantum dots (CQDs) are noted for low toxicity, high solubility, and stability. They've been used in biosensors detecting acrylamide in food and achieving a limit of 2.41×10^{-8} M. ZnO QD biosensors detect cysteine with a limit of 0.642 μM, while graphene quantum dots (GQDs) enable early lung cancer detection at 0.09 pg/mL. Textile-based sensors integrate Prussian blue with CdSe and rGO QDs for glucose and H_2O_2 detection, showing high sensitivity. [1] [2]

Cell-based biosensors: Cell-based biosensors (CBBs) connect to live cells or cellular constituents such bacteria, plant cells, and enzymes via transducers in order to detect specific analytes. They are employed in bioprocessing, medicine, food safety, industry, and environmental monitoring because of their small size and effectiveness in mimicking biological processes. To swiftly identify poisons in food, for instance, luminous microorganisms with reporter proteins use colorimetric or luminescence signals. Saccharomyces cerevisiae (yeast) biosensors have a high sensitivity of 0.32 ppm for copper ion detection by colorimetric and olfactory outputs. Bioluminescent Escherichia coli sensors, which have a dynamic range of up to 0.25 μg/L and are helpful for environmental monitoring, may detect mercury in water. [1]

1.2 Classification of biosensors based on main bioreceptor

Aptamers: Single-stranded DNA or RNA molecules known as aptamers are chosen using the SELEX procedure due to their high affinity and specificity for target molecules. Their compact size (usually between 30 and 100 nucleotides) enables effective surface immobilization. Transducers pick up on the conformational shift that occurs when an aptamer binds to its target.

Antibodies: Antibodies are proteins that work well in biosensors because of their strong binding affinity for particular analytes. There are two varieties of antibodies: polyclonal antibodies, which are more sensitive but less specific because they can recognize many epitopes on an antigen, and monoclonal antibodies, which are produced by a single type of immune cell and bind to one epitope.

Enzymes: Compared to conventional binding techniques, enzyme-based biosensors can reach lower detection limits due to the catalytic qualities of enzymes. Similar to a key opening a lock, enzymes can identify certain analytes and transform them into quantifiable products. They may also identify activators or inhibitors and evaluate alterations in the characteristics of the enzyme following analyte interaction.

Whole cell-based biosensors: Immobilized microorganisms such as fungi or bacteria are used by whole cell-based biosensors to identify target analytes. These biosensors, which belong to the nano/micro-biosensor class, are usually 0.5 to 5 micrometres in size. They need not have to be purified, which saves money and time and they can be combined with several kinds of transducers, like mass-based, electrochemical, and optical types. [3]

2. Environmental Contamination Detection via Nanomaterial-Enabled Sensors

Nanotechnology is pivotal in combating global air pollution by providing sensitive, real-time, and cost-effective alternatives to traditional monitoring methods. Nanosensors, including electrochemical, optical, electrical, and thermal sensors, detect pollutants with high sensitivity. Enzyme-based and DNA-based biosensors, along with nanobiosensors and cell-based biosensors, utilize nanomaterials and biological components for precise pollutant detection. These sensors are effective in detecting environmental contaminants at low concentrations in field settings, eliminating the need for expensive lab equipment. This review organizes sensors by specific analytes for environmental scientists and engineers, covering advancements in detecting pesticides, metals, and pathogens. [4] [5]

Pesticides: Detecting pesticides is crucial due to their toxicity and bioaccumulation potential. Electrochemical sensors immobilize acetylcholinesterase (AChE) on electrodes enhanced with nanomaterials like graphene oxide, gold nanoparticles, and carbon nanotubes for high sensitivity and rapid detection. Innovations include SERS sensors for organophosphates (OPs) and aptamer-based sensors for neonicotinoids. Competitive electrochemical immunoassays and plasmonic nanocomposites are used for triazine detection, achieving detection limits below EPA thresholds. [5]

Metals: Nano-enabled sensors detect heavy metals like mercury, lead, cadmium, and chromium using various transducers and nanoparticles. Lead sensors, for example, use DNAzyme, RCA, and quantum dots for a 7.8 pM detnges and advancements in the field. [5] [6]

2.1 Nanotechnology-Based Biosensors: Revolutionizing Diabetes Management Practices

An investigation into several glucose monitoring techniques was conducted, with a focus on accuracy and non-invasiveness. The Clark Enzyme Electrode, whose design improves signal stability, is used for continuous glucose monitoring. The Yellow Springs Instrument 2300 STAT PLUS is crucial for calibrating glucose test strips and validating other monitors. A flexible, self-powered glucometer uses enzyme reactions in nanowires to provide real-time, continuous monitoring. Mediated biosensors improve sensitivity by transferring electrons between enzymes and electrodes. $ZnFe_2O_4$ Magnetic Nanoparticles and Carbon Nanotubes in chitosan solutions are used for non-invasive urine glucose detection, offering high sensitivity and selectivity. An electronic nose assesses urine odour to detect glucose levels, and a smartphone's ambient-light sensor is utilized for a portable, colorimetric urine glucose test. These methodologies aim to improve the reliability and ease of glucose monitoring. [7]

2.2 Advancements in Biological Imaging Using Nucleic Acid-Based Nanodevices

Visualizing structures at the nanoscale scale, which is generally less than 100 nanometres, is the primary objective of the imaging area known as nanoimaging. It entails observing and working with materials at the atomic and molecular levels using sophisticated methods and instruments. For disciplines like biology, materials science, and nanotechnology, this capacity is essential. [8] [9]

2.3 Imaging using Atomic Force Microscopy (AFM)

Atomic Force Microscopy (AFM) is crucial for imaging DNA and RNA due to their nonconductive nature and consistent size. Using a sharp probe tip, AFM scans surface to measure distances and detect topography accurately. Tapping mode AFM is widely used in physiological studies to map surface contours precisely. In nucleic acid research, AFM visualizes DNA complexes, enzymatic processes, and structural DNA nanotechnology, facilitating the creation of precise 1D, 2D and 3D DNA structures. High-speed AFM (HS-AFM) achieves single-molecule resolution, capturing dynamic processes such as enzymatic reactions on DNA origami nanodevices in real-time. HS-AFM has revealed protein-DNA interactions, conformational changes like G-quadruplex formation induced by HIV-1 nucleocapsid proteins, and steps in transcription and DNA recombination. Overall, AFM and HS-AFM significantly advance molecular biology by elucidating nucleic acid structures and their interactions with proteins. [9]

2.4 Cancer Cell Membrane Imaging

Cellular fluorescence imaging is a critical technique in biosensing and early disease diagnosis due to its capability to provide visual biodistribution, real-time feedback, and operational ease. This imaging technique enables real-time imaging of cell-specific molecular targets, pathways and physiology in addition to the simultaneous detection of numerous targets. These characteristics make it possible to diagnose and track diseases early and accurately. An important part of this process is the use of fluorescent labelling techniques, which includes the covalent or non-covalent attachment of fluorescent groups to molecules like proteins and nucleic acids.

DNA fluorescence labelling is a widely used bioanalysis and imaging technique. Environmentally sensitive fluorophores change observable fluorescence attributes including intensity, wavelength, or lifetime to detect interactions between DNA and other biological molecules. This sensitivity allows for the visualization and monitoring of complex biological processes on cell membranes. [9] [10]

2.5 DNA Nanodevices for Probing the Cellular Membrane Microenvironment

The cell membrane, comprising lipids, proteins, and carbohydrates, regulates ion and nutrient exchange, maintaining cell shape and function. It also supports internal stability, cellular connections (like adhesion and communication), and crucial processes such as signal transduction and substance transport. Traditional techniques like flow cytometry and mass spectrometry have limitations in monitoring membrane dynamics, necessitating advanced biosensing tools for comprehensive cellular understanding. Functional nucleic acids like DNAzymes and aptamers are versatile beyond genetics. They respond to stimuli and exhibit specific chemical recognition, pivotal for designing dynamic DNA nanostructures. Nanostructures such as aptamers and G-quadruplexes are instrumental in bioanalysis, sensing, and medical applications due to their responsiveness to external triggers. However, DNA's negative charge impedes direct interaction with similarly charged cell membranes, posing challenges for integrating DNA nanodevices onto cell surfaces. Overcoming this challenge involves techniques like hydrophobic insertion, embedding hydrophobic DNA modified with molecules like cholesterol and C18 lipids into the lipophilic phospholipid bilayer. Methods like liposome fusion and lipofection utilize non-covalent molecular interactions to incorporate DNA into membranes. For stable DNA attachment to cell surfaces, strategies include using aptamers selected through Cell-SELEX and DNA-antibody conjugates. These methods exploit specific ligand-receptor interactions and strand displacement events. Covalent conjugation modifies synthetic nucleic acids with functional groups (e.g., amine or sulfhydryl) that chemically bond with amino acid residues on membrane proteins. These

advancements enhance DNA nanodevice functionality and enable targeted interactions, opening new avenues for medical and biological research. [11] [12]

2.6 ATP-Gated DNA Nanodevice for Amplified Fluorescence Labelling of Cancer Cells

In this study, a dual module DNA nanodevice that targets membrane proteins and is activated by ATP is used to identify cancer cells with fluorescence that is amplified. This nanodevice operates via a "AND" logic gate mechanism and recognises extracellular ATP and cancer cell membrane proteins using dual aptamers. Its design allows for precise and versatile identification of various cancer cells by responding to ATP levels typical of tumor environments, ensuring high specificity and sensitivity. This innovative approach offers a promising strategy for precise tumor imaging and ATP-regulated cancer treatment. [13]

The experimental section details methodologies to validate the nanodevice's functionality, including materials, cell culture, atomic force microscopy, and cytotoxicity evaluation of ATP. For gel electrophoresis, aptamers and HCR components were prepared, hybridized, and analysed using PAGE. Confocal fluorescence microscopy imaged labelled cell membranes, while cell viability was assessed under various ATP concentrations, ensuring high viability. Flow cytometry confirmed significant fluorescence intensity shifts in treated cells, demonstrating the combined action of the anchoring and ATP switch modules. Optimization of probe concentration and incubation time identified optimal conditions for fluorescence response. These experiments validated the nanodevice's assembly, specific recognition, and signal amplification capabilities for cancer cell identification and imaging [13] [14]. We summarize some of the different cellular tumor microenvironments for ATP imaging in Table 1. [11]

Table 1. Summary of the ATP imaging of the cell membrane. [11]

Target	Linear Range	Cell Type
ATP	0–1000 μM	MDA-MB-231
ATP	5–60 μM	A549
ATP	10–100 nM	SMMC-7721
ATP	0–500 μM	HeLa
ATP	0–5 mM	HeLa

2.7 Harnessing Bioelectricity in Nanotechnology for Cancer Dynamics

The bioelectrical characteristics of cancer cells profoundly influence their behaviour and interactions with their environment. Gap junctions, formed by connexins, facilitate the spread of bioelectrical activity among cancer cells, crucial for metastasis, invasion, and tumor growth. Understanding these phenomena holds promise for advancing cancer treatment strategies and understanding cancer pathogenesis. Non-excitable cancer cells emit static electric signals smaller

than those seen in excitable cells, posing challenges for electrophysiological recording. Traditional methods like patch clamp, microelectrode arrays (MEAs), impedance spectroscopy, and fluorescence imaging have limitations in sensitivity, throughput, and long-term recording. Novel nanotechnologies are being developed to enhance the recording of bioelectrical properties in non-excitable cells, particularly in cancer research. In cancer biology, bioelectric aspects play a pivotal role. Gap junctions facilitate electrical signalling between cancerous and non-cancerous cells, influencing tumor progression by promoting pro-tumoral behaviours via interactions with stromal cells. Cancerous tissues exhibit altered ionic environments and transepithelial potentials, creating local electric fields that enhance migration and invasion. Electrophysiological characteristics vary between cancer types and even between tumors on different body sides (e.g., left vs. right-sided breast cancer), with early-stage cancer cells often showing depolarization, critical in tumorigenesis. Cancer stem cells exhibit unique electrophysiological patterns, maintaining an undifferentiated state through membrane depolarization, crucial for tumor initiation, growth, recurrence, and treatment resistance. Endogenous electric fields influence cancer cell migration, modulated by external electric fields. Ion channels and the ECM composition are critical in cell mobility and metastatic potential. Technological advancements have improved the study of cancer bioelectricity, enabling precise identification and tracking of electrical activity in cancer cell populations and tissues, offering insights for therapeutic applications. [15]

2.8 Emerging Nanotechnologies Transforming Cellular Electrophysiology Research

In bioelectrical research, several techniques offer distinct advantages and limitations for studying cellular activity. Patch clamp involves placing a glass micropipette on the cell membrane to achieve precise recordings of intracellular signals, making it highly sensitive and accurate for measuring ion channel activity and membrane potential changes. However, it suffers from low throughput and is not suitable for long-term recordings. Microelectrode arrays (MEAs) enable simultaneous recording of extracellular electrical activity from multiple cells using numerous electrodes, offering high throughput capabilities. Yet, MEAs are less sensitive, primarily suited for high-frequency signals in excitable cells and less effective for static signals in non-excitable cells. Impedance spectroscopy measures cell electrical impedance under current stimuli to deduce information about cell characteristics but may alter cell behaviour due to applied stimuli. Fluorescence imaging uses voltage-sensitive dyes for optical imaging of membrane potential changes, but chemical interactions with cells can affect natural activity, and it has limitations in cumulative bioelectrical activity recording. Each technique thus presents unique opportunities and challenges in advancing our understanding of cellular bioelectricity action limit. Cadmium

detection utilizes CdTe/CdS QDs and ratio metric sensors, achieving 6-12 nM detection limits. Chromium detection employs immunochromatographic assays with monoclonal antibodies, offering rapid visual detection in minutes. [5]

2.9 Pathogens

Detecting waterborne pathogens like Vibrio cholerae, Legionella pneumophila, and Pseudomonas aeruginosa is critical. Nanosensors target Vibrio cholerae and cholera toxin, using fluorescence resonance energy transfer (FRET) with detection limits of 280 pM. Comprehensive reviews by experts provide detailed insights into these pathogen detection methods, addressing the challenges. [16]

3. Overviews of Sensors in Biomedical Sector

3.1 Advances in Lactate and Glucose Monitoring

Monitoring of lactate and glucose the monitoring of athletic performance tissue oxygenation and diabetes management are changing as a result of the combination of cutting-edge biosensors with neural networks and computational approaches just as glucose biosensors tuned by machine learning algorithms provide more accuracy and sensitivity enabling improved blood glucose level monitoring and control lactate biosensors provide real-time insights into lactate levels aiding both exercise and medical diagnoses. [17]

Disease diagnosis: Biosensors are crucial for diagnosing diseases and monitoring treatment responses, as they can detect specific biomarkers for early and accurate diagnosis of conditions like cancer and infectious diseases. Techniques like electrophysiological recording and impedance spectroscopy show that cancer cells have higher membrane impedance and different conductive properties, aiding in cancer detection. Impedance imaging visualizes the electrical properties of tissues to identify cancerous areas. [17]

Detection of Biomolecules: Nanopores detect amino acids, peptides, and proteins through ion current signals, identifying substances like oligosaccharides and polymers. Nanogaps use tunnelling current signals to detect nucleic acids, peptides, and second messengers such as ATP and cyclic AMP. Nanopipettes characterize ion current signals in polymers like poly-L-lysine. [18]

Cancer treatment: Emerging treatments are using electric fields to disrupt cancer cell activities by targeting ion channels to induce selective cell death. Electroceuticals employ electrical signals to manipulate cellular behaviour, potentially enhancing immune responses and boosting the effectiveness of traditional treatments like chemotherapy. Bioelectric signals also influence cellular functions such as division, migration, and apoptosis. Understanding these signals can

provide insights into cancer mechanisms and lead to new treatment strategies. [15]

Medical Diagnostics: Nanodevices are ideal for comprehensive medical diagnostics due to their ability to detect multiple markers simultaneously, enabling early disease detection and precise medical interventions. They can develop highly sensitive biosensors for detecting diseases at the molecular level, such as DNA-based logic gates that identify multiple biomarkers. Nanobiosensors can detect cancer biomarkers at very low concentrations, using quantum dots and gold nanoparticles for high-contrast imaging. They also enable rapid detection of pathogens like viruses and bacteria, with silver nanoparticles enhancing sensitivity for diseases like HIV and COVID-19. These sensors are used for identifying serum carcinogens, antigens, and metabolic disease-causing organisms, making them suitable for routine diagnostics and point-of-care testing for conditions like diabetes, cardiovascular diseases, and infections. Incorporating nanoparticles improves the reuse and recycling of enzymes, enhancing the efficiency and cost-effectiveness of tests. [18]

Targeted Drug Delivery: Biomolecular computing systems can design smart drug delivery mechanisms that release therapeutics in response to specific cellular signals, enhancing treatment efficacy and minimizing side effects. NPs are excellent water-soluble carriers that can be used for targeted drug delivery. They can transport drugs directly to tumor sites, minimizing side effects on healthy tissues. A range of nanoparticle forms, including liposomes, nanogels, micelles, and dendrimers, have been used because of their excellent endocytosis capabilities and great biodegradability. These structures improve the effectiveness and delivery of medicinal substances such as antigenic proteins, aptamer sequences, and small molecule medicines. [19]

Alcohol Detection: Alcohol biosensors measure alcohol concentrations in beverages and biological samples, important for quality control in the food industry and monitoring blood alcohol content in forensic settings. These sensors are used to detect pathogens, toxins, and other contaminants in food products, ensuring food safety and quality. They help in maintaining public health by preventing foodborne illnesses and ensuring compliance with safety standards. [20]

Pathogen Detection: These sensors help in identifying foodborne pathogens like E. coli and Salmonella, preventing outbreaks of foodborne illnesses. [17]

3.2 Nucleic Acid-Based Probes and Detection Technologies

Nucleic acid-based probes, such as molecular beacons and catalytic molecular beacons, are valuable for detecting mutations and genetically modified targets due to their functionalization and enzymatic properties. Algorithms for probe selection and target classification enhance nucleic acid-based systems, while electrochemical detection offers greater specificity and sensitivity.

These advancements facilitate high-throughput screening, mutation monitoring, GMO detection, and biosensor applications for secure identification and genetic studies. [21]

3.3 Paper-Based Sustainable Biosensors

Paper-based biosensors employ electrochemical detection for high selectivity, sensitivity, and low cost. Innovations include devices detecting nerve agents, EGFR mutations, progesterone, and phenolic compounds using advanced materials like carbon black/Prussian Blue nanocomposites and 3D-printed hydrophobic patterns. These methods create portable, affordable biosensors for diverse applications. [22]

3.4 Nanotechnology in Diabetes Management

The prevalence of diabetes necessitates effective glucose monitoring tools. Biosensors, particularly those incorporating nanomaterials, are crucial for early detection and management. Advances in non-invasive, continuous glucose monitoring improve patient comfort and clinical outcomes, integrating biosensors into personalized medicine for better healthcare system benefits. [7]

3.5 Cellular and Live Cell Imaging

Cellular and live cell imaging techniques are crucial for understanding cell structure and function by visualizing cellular components and their spatial organization. For fixed cells, methods like fluorescent in situ hybridization (FISH) visualize endogenous nucleic acids, revealing the distribution of DNA and RNA. Super-resolution imaging techniques such as STORM and DNA-PAINT exceed traditional microscopy limits, providing detailed views of subcellular structures.

Live cell imaging enables real-time observation of dynamic cellular processes. Antisense-based recognition detects target RNAs by hybridizing antisense oligonucleotides with specific RNA sequences, while protein-based RNA recognition uses fluorescent proteins fused with RNA-binding proteins to visualize RNA dynamics. Aptamer-based recognition, such as Spinach aptamers, binds to specific fluorophores for real-time imaging of RNA molecules. Small molecule visualization involves allosteric Spinach-based sensors and Spinach riboswitches, which identify cytosolic compounds and metabolites by altering fluorescence upon binding to target molecules. DNA nanodevices can serve as probes for quantitative imaging of small molecules in subcellular organelles, equipped with fluorescent tags to track interactions with the cellular environment. These combined methods are powerful tools for cellular research. [9]

3.6 Electrical Properties of Cancer Cell Populations and Tissues

Future explorations in cancer research could focus on various aspects of cellular electrophysiology. Investigating the expression levels of connexins and the presence of gap

junctions in different cancer cell lines can provide insights into cell communication and tumor progression. Voltage-sensitive dye imaging can be utilized to visualize the electrical state of cells and tissues, capturing depolarization events during tumorigenesis. Electrotaxis studies, which involve applying external electric fields, can help observe cell migration responses and metastatic behaviour. Monitoring ion channel activity is crucial for understanding their role in cancer cell proliferation, migration, and stemness. Additionally, exploring how the extracellular matrix (ECM) composition affects the bioelectrical properties and migratory behaviour of cancer cells can shed light on the complex interactions within the tumor microenvironment.

Table 2 shows the different types of nanobiosensors in biomedical applications [8] other than the ones discussed in this paper.

Table 2. Different types of nanobiosensors in Biomedical applications **[8]**

Nanobiosensor	Nanomaterials Used	Type of Sensor	Application (Detection)	Limit of Detection (LOD)
Antibiotic residue sensor	Au, Pt and SiO_2 NPs	Nano enzyme coupled with MIP as a bio-inspired body	Sulfadiazaine	IC15:0.08mg and IC506.1mg/L
AChE	DNA based materials	Electrochemical	Phytophthorapulmivora causing black pod root in cacao pod	-
QD nanosensor	Gold nanoparticles	Immunosensor	Mycotoxins ZEA, DON, FB1/FB2	-
QD nanosensor	QDs	Fluorescence	Pathogens	-
Artificial nasal sensor	Carbon	Profile of volatile organic compounds	Pathogens depending on the organic compounds released	Sensitivity of 85% to 95%
Acetylcholinesterase on white paper using indophenol acetate	Enzyme	Coloured antiphoton	Paraoxon	3.5 g/L
AChE	SMWCNTs	Electrochemical	Methylparathion, parathion and paraoxan	0.4pM
Surface plasmon resonance (SPR)	MWCNTs	SPR	Cymbidium Mosaic virus	-
Nucleic acid nanosensor	CNTs	Immunosensor	Ganoderma boninse	0.2ng/L
QD nanosensor	Quantum dots	Fluorescence	Pathogens and viruses	-

4. Conclusions

Through the use of extremely sensitive nanosensors, nanodevices are revolutionising diagnostics by enabling early illness diagnosis. Small amounts of biomarkers, which are important in the early stages of diseases like cancer, can be detected by these devices, allowing for an earlier diagnosis and the start of therapy, which may greatly improve patient outcomes. Furthermore, with developments like quantum dots, nanotechnology improves sensitivity and resolution of conventional imaging methods like fluorescence imaging, magnetic resonance imaging, and CT scans. This allows for the precise visualisation of diseases at the molecular level. Nanofluidic devices are advantageous for advanced diagnostics because they consolidate several laboratory operations onto a single chip, enabling quicker and more effective biological sample analysis. These lab-on-a-chip devices play a critical role in the point-of-care diagnosis of infections, genetic diseases, and other ailments, providing prompt and reliable diagnoses that are essential for timely clinical decision-making. Gold nanoparticles further enhance diagnostics by detecting specific biomarkers with high sensitivity and specificity, aiding in the diagnosis of diseases like heart disease and diabetes. Nanodevices also advance genetic screening and in vivo monitoring. Nanopore sequencing enables rapid DNA and RNA analysis, identifying genetic mutations linked to hereditary diseases swiftly. In vivo monitoring using nanorobots provides continuous real-time data on physiological conditions, offering insights into disease progression and treatment efficacy.

These nanotechnological innovations improve upon traditional diagnostic methods, offering precise, sensitive, and rapid detection capabilities that can lead to improved patient management and outcomes. Challenges in monitoring cell membrane microenvironments with DNA nanodevices include stability, targeting specificity, and real-time monitoring. Chemical modifications like phosphorothioate linkages or locked nucleic acids enhance stability against nucleases, critical for ensuring longevity and reliability in diagnostic applications. Targeting specificity is achieved through engineering DNA nanodevices with high-affinity ligands like aptamers, tailored to respond to unique environmental stimuli of target cells. Integrating multiple functionalities into a single DNA nanodevice involves developing modular designs for easier integration and utilizing DNA logic gates for complex signal processing. High-resolution imaging of cellular processes requires advanced fluorescence techniques, utilizing dynamic DNA nanodevices that change conformation in response to stimuli, ensuring accurate and real-time monitoring without adverse immune responses or interference with normal cell functions. Nanotechnology extends to environmental applications, employing nanomaterial-enabled sensors for monitoring water quality, detecting pollutants in air and soil, and identifying hazardous

substances such as explosives and industrial compounds with high sensitivity and rapid response times. These sensors play a crucial role in environmental remediation processes, ensuring pollutant removal effectiveness and meeting safety standards. In forensic science, paper-based biosensors detect minute traces of biological or chemical evidence, aiding in crime scene investigations and toxicology. Consumer applications include integrating biosensors into smart packaging to monitor product freshness and safety, ensuring quality control in perishable goods.

Wearable technology integrates genetic and metabolic profiling for continuous health monitoring, offering insights into vital signs, glucose levels, and hydration status for comprehensive health management. In medical fields like elderly care, implantable biosensors track biomarkers and administer medication based on real-time data, enhancing disease prognosis and treatment efficacy. Biosensors also play a crucial role in surveillance systems for tracking infectious diseases and monitoring astronauts' health in space environments. Future explorations in cellular electrophysiology hold promise for enhancing treatments in cardiology, neurology, and regenerative medicine through advanced electrophysiological techniques, improving patient outcomes and enabling the development of bioengineered tissues and organs with integrated electrical properties. These advancements underscore the transformative potential of nanotechnology in diagnostics, environmental monitoring, consumer products, and medical applications, paving the way for more efficient, sensitive, and personalized approaches to healthcare and environmental management.

Author contributions

Dr. Neeta Shivakumar: Conceptualization, Supervision, Validation, Writing – review & editing

Pranay Prasad: Resources, Writing – original draft, Data curation

Riya Prince: Resources, Writing – original draft

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Conflicts of interest

The authors declare that they have no conflict of interest.

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