ISSN 1996-0700

Asian Journal of Biotechnology

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OPEN ACCESS Asian Journal of Biotechnology

ISSN 1996-0700
DOI: 10.3923/ajbkr.2026.1.15

Review Article
Nanotechnology in Smart Implants and Biosensors: Advances, Applications and Future Perspectives

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Abstract

Nanotechnology-enabled smart implants and biosensors are emerging as transformative technologies in modern healthcare, offering new opportunities for precision diagnosis, real-time health monitoring, targeted therapy and personalized medicine. This review critically examines recent advances in nanotechnology-based smart implants and biosensors, with particular emphasis on their biomedical applications, technological developments, challenges and future perspectives. The reviewed literature indicates that nanomaterials, including graphene, carbon nanotubes, quantum dots and other nanostructured materials, can enhance the sensitivity, selectivity, biocompatibility and multifunctionality of biosensing platforms for the detection of clinically relevant biomolecules. In smart implants, nanostructured coatings can improve cellular adhesion and tissue integration while potentially reducing undesirable inflammatory and immune responses. Nanotechnology also supports the development of self-powered implants through piezoelectric and triboelectric energy-harvesting systems and facilitates targeted, controlled and stimuli-responsive drug delivery. Collectively, these advances demonstrate the potential of nanotechnology to integrate sensing, therapeutic delivery, energy harvesting and biological interfacing within next-generation implantable systems. However, challenges related to long-term biosafety, biocompatibility, device stability, reproducibility, scalable manufacturing, cost and regulatory approval continue to impede clinical translation. Future research should prioritize long-term in vivo validation, standardized safety assessment, scalable fabrication and integration with artificial intelligence and personalized healthcare technologies. Overall, nanotechnology offers substantial potential for developing intelligent, minimally invasive, self-powered and patient-specific smart implants and biosensors, although continued interdisciplinary research is required to achieve reliable clinical implementation.

Key words: Nanotechnology, biosensors, drug delivery system, biomolecules, piezoelectric, triboelectric nanogenerators

Citation: Kumari, M., Dinesh, A. Sharma and A. Sharma, 2026. Nanotechnology in smart implants and biosensors: Advances, applications and future perspectives. Asian J. Biotechnol., 18: 1-15.

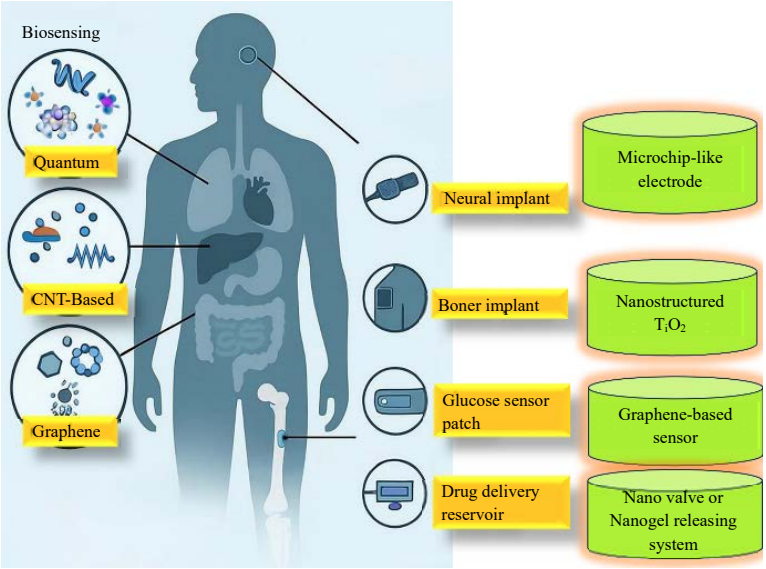
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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

GRAPHICAL ABSTRACT



INTRODUCTION

The remarkable progress of nanotechnology has transformed biomedicine by facilitating the fabrication of extremely effective smart implants devices and biosensors with improved functionality, greater sensitivity and biocompatibility. The distinctive physicochemical characteristics of nanomaterials, as their increased surface-to-volume ratio, tuneable surface chemical properties, remarkable electrical conductivity and mechanical strength, have markedly enhanced the efficacy of traditional biomedical devices. Researchers have developed advanced implants by incorporating materials including metal and metal oxides, quantum dots, polymeric nanocomposites and two-dimensional materials, which enhance tissue regeneration, reduce infection and enable real-time physiological monitoring.

Nanoparticle-based drug delivery strategies have been developed to overcome these limitations, offering a promising approach to enhancing drug transport across the BBB and potentially transforming stroke treatment. Additionally, nanotechnology is revolutionizing the fields of smart implants and biosensors, driving breakthroughs in precision medicine, real-time health monitoring and disease management. By leveraging nanotechnology, researchers aim to improve drug delivery efficiency and optimize formulations for successful clinical translation. However, further advancements are necessary to refine these approaches, ensuring their effectiveness and feasibility in real-world medical applications[1]. Biosensors are advanced engineering tools with diverse applications across industries such as healthcare, environmental monitoring, military, food quality control and microbiology. They play a crucial role in detecting pollutants, toxic elements, biohazards and biomolecules for clinical diagnostics and medical examinations. Due to their ease of use, scalability and cost-effectiveness, biosensors have gained prominence in modern medical technology. The integration of nanotechnology has significantly enhanced biosensor performance, enabling the detection of single biomolecules with high sensitivity and rapid analysis. Nanomaterials such as nanoparticles, nanowires, carbon nanotubes (CNTs), nanorods and quantum dots (QDs) are widely used in nano-biosensors due to their large surface area, stability and excellent electrical and thermal conductivity[2]. The development of implantable biosensors for continuous metabolite monitoring is a growing area of scientific and technological interest. Nanotechnology, which focuses on material properties at the nanoscale, is emerging as a key tool to enhance biosensor performance. A major focus is on electrochemical detection, given its widespread use and significant enhancements through nanotechnology. Additionally, challenges related to the toxicity and biocompatibility of nanomaterials are discussed, along with prospects for nanotechnology applications in implantable biosensors[3]. This review offers a thorough examination of recent advancements in nanotechnology for smart implants and biosensors, emphasizing the importance of nanomaterials to device performance, addressing current applications in biomedical devices and analysing the challenges and prospects that will influence the forthcoming era of precision healthcare technologies.

BIOSENSOR DESIGN AND PRINCIPLE

A biosensor detects physical changes, including heat, force, pressure, movement, humidity and electrical components like current[4]. A sensor is a device or module that transforms these measurements into detectable and interpretable signals. A biosensor is a receptor-transducer device that converts a biological reaction into an electrical signal. Biosensor development and advancement have recently become a major focus for researchers and scientists due to their wide range of applications, which include healthcare and disease detection, environmental surveillance, monitoring water and food quality and facilitating drug delivery. Biosensors come in many shapes and sizes, capable of measuring samples such as pathogens and toxicants at very low concentrations. A biosensor is made up of five key parts: The analytical agent, which is the chemical substance that is recognized and quantified; the target's receptor, which communicates specifically with the target; the transducer, the device which alters variations in the sample into quantifiable signals; the electrical system, which processes and monitors these signals; and, finally, a display unit or detector, which displays the results in a readable format[5]. Sensor technology development has grown increasingly significant due to a variety of applications, including environmental and food quality monitoring, medical diagnosis and health care, automotive and industrial manufacturing, space, defense and security.

CLASSIFICATION BASED ON DETECTION METHODS

Biosensors are classed according to their shape, size and structure. These classifications can be categorized on the basis of bioreceptor, sample to be analyzed, energy source, analog or digital sensors and signal detection. On the basis of bioreceptors, biosensors can be subcategorized into immunosensors, enzymatic biosensors, aptamer-based biosensors and nucleic acid biosensors. They are separated into four types under the transducer category: Thermal, optical, acoustic and electrochemical biosensors. A few biosensors, such as electrical, optical, thermal, acoustic, magnetic and mechanical biosensors, are further separated according to their modes of detection. The optical biosensors can be further separated into four categories: Optical fiber-based, chemiluminescence-based, fluorescence-based and SPR-based. Figure 1 shows the classification of sensors based on the above-mentioned characteristics.

Electrochemical biosensors: Accurate and early cancer diagnosis is crucial for successful treatment, yet conventional diagnostic methods often suffer from drawbacks like invasiveness, high costs and limited sensitivity for early detection. Electrochemical biosensing has emerged as a promising alternative, offering rapid, sensitive and cost-effective detection of cancer biomarkers[6]. This review highlights how electrochemical biosensors provide real-time molecular insights through precise target recognition and signal transduction. The integration of advanced materials, nanotechnology, microfluidics and AI has significantly enhanced the performance and clinical potential of these biosensors. Despite challenges in commercialization and practical implementation, ongoing research suggests a strong future for electrochemical biosensors in personalized oncology diagnostics[7]. Recent developments in wearable electrochemical biosensors have significantly transformed the landscape of personalized and preventive healthcare by enabling continuous, on-body monitoring of critical biomarkers. Initially led by glucose sensing technologies, wearable biosensors have rapidly evolved to detect a broader spectrum of analytes, including small molecules, hormones, drugs and macromolecules found in various biofluids such as sweat, saliva, tears, wound exudate and interstitial fluid. These biosensing platforms are engineered using sophisticated components such as specific biorecognition elements, advanced signal transduction methods, innovative electrode materials and flexible substrates. Cutting-edge fabrication techniques have further enhanced the miniaturization, sensitivity and wearability of these devices. Additionally, recent innovations have introduced features like multi-sensory integration, closed-loop control systems for drug delivery and improved power solutions, making these devices more autonomous and intelligent. However, the field still faces significant challenges related to biocompatibility, biofouling and long-term sensor stability. To address these, ongoing research is leveraging advances in materials science, nanotechnology and artificial intelligence, aiming to improve sensor performance and durability. Overall, wearable electrochemical biosensors represent a promising frontier in real-time, non-invasive health monitoring and personalized medicine[8]. In the wake of the COVID-19 pandemic, the demand for highly sensitive, miniaturized and non-destructive diagnostic tools has surged, leading to a growing interest in nanomaterial-coated paper-based electrochemical biosensors. These biosensors offer enhanced specificity, sensitivity, robustness and reproducibility due to the incorporation of functional nanomaterials. Environmentally friendly and cost-effective, paper-based electrodes (PEs) eliminate the need for

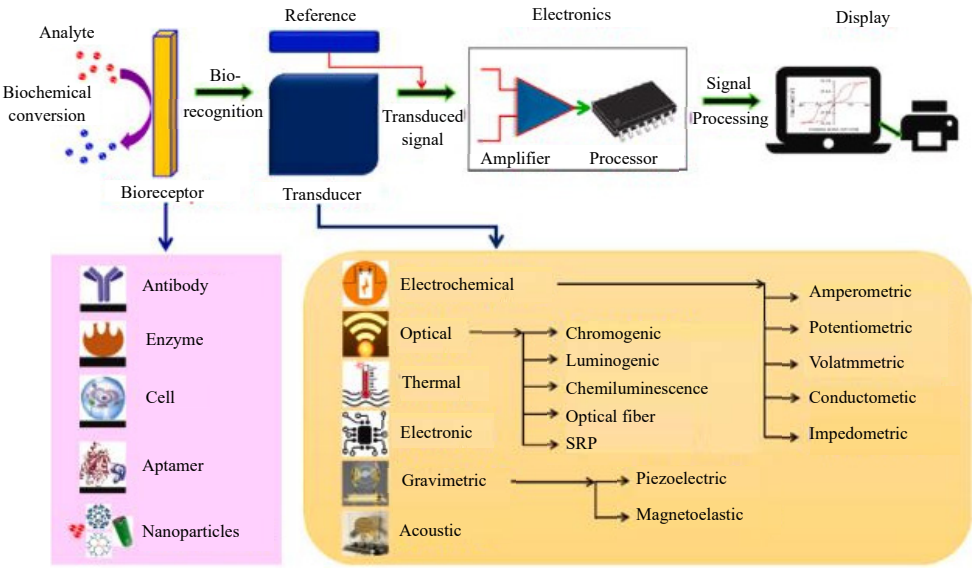


Fig. 1: Classification of sensors based on the above-mentioned characteristics

external pumps by utilizing capillary action and enable reagent-less and multiphase detection through innovative origami designs[9]. *In vivo* electrochemical sensing has become an essential tool for real-time monitoring of neurotransmitters, neuromodulators and metabolites within the central nervous system. Voltammetry, amperometry, potentiometry, Field-Effect Transistors (FETs) and Organic Electrochemical Transistors (OECTs) technologies provide powerful tools for real-time monitoring of neurotransmitters and metabolites in the brain, aiding in the understanding of neural function and disorders. These technologies enable detection from single cells to entire brain systems, offering varying advantages: Voltammetry for miniaturized electrodes in complex matrices, amperometry for high temporal resolution and potentiometry for less invasive quantitative analysis. The FETs and OECTs offer enhanced signal amplification and sensitivity. Flexible electronics have revolutionized information and communication technologies, especially in healthcare through wearable devices integrated with electrochemical biosensors for real-time, point-of-care disease diagnosis. To enhance sensitivity without compromising flexibility, recent innovations incorporate advanced nanomaterials and nanotechnologies. The key fabrication techniques, such as nanolithography and nano/microneedle-based patches, are recent developments in wearable biosensors for diabetes and dermatitis. It also explores emerging trends in nanotechnology-enabled nanopatterning and needle-based platforms, proposing innovative strategies for creating sensitive, wearable diagnostic tools suitable for point-of-care testing (POCT)[10].

Potentiometric biosensors: Potentiometric biosensors are analytical devices that combine a biological recognition element (such as enzymes, antibodies, or microorganisms) with a potentiometric transducer to detect specific analytes by measuring changes in electric potential. These biosensors operate based on the detection of ionic species or redox-active substances that influence the potential difference between a reference electrode and a working electrode. The most common configurations include Ion-Selective Electrodes (ISEs) and Field-Effect Transistors (FETs), Especially Ion-Sensitive Field-Effect Transistors (ISFETs), which are widely used for monitoring pH, urea, glucose and other biologically significant molecules[11,12].

Potentiometric biosensors offer several advantages, such as high sensitivity, low power consumption, miniaturization potential and rapid response times. They have found extensive applications in clinical diagnostics, environmental monitoring and food safety. However, challenges remain in terms of long-term stability, selectivity in complex matrices and interference from background ions. Recent advancements include the integration of nanomaterials (graphene, carbon nanotubes) and microfluidic platforms to enhance performance and portability. Ongoing research continues to focus on improving biocompatibility and sensor lifetime for real-time and in vivo applications.

Amperometric biosensors: Amperometric biosensors are analytical devices that measure current produced by the oxidation or reduction of an electroactive species in response to a biological reaction[13]. These biosensors operate under a constant potential applied between a working and a reference

electrode, where the current generated is directly proportional to the concentration of the target analyte. The key component of an amperometric biosensor is the biorecognition element (such as enzymes, antibodies, or microbial cells) that catalyses a specific reaction, leading to the production or consumption of electroactive species. Common examples include glucose biosensors, where the enzyme glucose oxidase catalyses the oxidation of glucose, producing hydrogen peroxide, which is then electrochemically detected[14].

Amperometric biosensors are extensively utilized in medical diagnosis, environmental surveillance, food quality assessment and bioprocess monitoring owing to their exceptional sensitivity, quick response and ability for miniaturization. Recent advancements in nanomaterials, including carbon nanotubes, graphene and metal nanoparticles, have markedly improved the efficacy of amperometric biosensors by augmenting electron transfer rates and expanding the surface area for biomolecules immobilization[15]. Additionally, the development of flexible and wearable biosensors has opened new avenues for continuous and non-invasive monitoring of biomarkers in real-time. Despite their numerous advantages, challenges such as interference from non-target species, enzyme stability and limited selectivity still require ongoing research and innovation.

Conductometric biosensors: Conductometric biosensors are a type of electrochemical biosensor that measure changes in the electrical conductivity of a solution resulting from a biochemical reaction between the target analyte and a biorecognition element. These biosensors operate by detecting variations in the concentration of ionic species produced or consumed during enzymatic or biochemical reactions. When an analyte interacts with the immobilized bioreceptor (enzyme, antibody, or aptamer), the ionic composition of the medium changes, leading to a measurable change in conductivity. Due to their simple design, rapid response and ability to function without reference electrodes, conductometric biosensors have been effectively applied in environmental monitoring, food quality control and medical diagnostics[16].

Recent advances in nanomaterials and microfabrication technologies have enhanced the sensitivity, selectivity and miniaturization of conductometric biosensors. Integration with nanostructured materials like carbon nanotubes, graphene and metal nanoparticles has significantly improved signal transduction by enhancing electron transfer and surface area for immobilization. These biosensors are particularly advantageous for detecting analytes such as urea, glucose, pesticides and heavy metals in complex matrices. Furthermore, their label-free detection, low cost and potential for integration into portable devices make them promising tools for point-of-care diagnostics and in-field applications. Despite some limitations in selectivity and environmental interference, ongoing research is addressing these challenges through the development of advanced bioreceptor interfaces and signal amplification strategies.

Impedimetric biosensors: Impedimetric biosensors are a category of sensors that function by measuring alterations in the electrical impedance at the sensor interface due to biological phenomena. These types of sensors typically employ an electrode surface modified with biorecognition components, including antibodies, enzymes, or DNA probes. The binding of the target analyte to the biorecognition component modifies the interfacial characteristics of the electrode, resulting in a quantifiable change in impedance. Impedance spectroscopy (IS) is frequently utilized to observe these alterations over a spectrum of frequencies, facilitating label-free, real-time identification with elevated sensitivity[17].

One of the major advantages of impedimetric biosensors is their label-free detection capability, eliminating the need for secondary reagents or fluorescent tags. This simplifies the assay design and reduces the cost and time of analysis. Additionally, their miniaturization potential makes them ideal for point-of-care applications. However, challenges such as non-specific binding, electrode fouling and the need for precise surface modification remain areas of ongoing research. Recent advancements in nanomaterials, such as the use of gold nanoparticles, carbon nanotubes and graphene, have significantly improved the sensitivity and stability of impedimetric biosensors, expanding their application in clinical diagnostics and environmental monitoring.

NANOMATERIALS IN SMART IMPLANTS AND BIOSENSORS

Biosensors are advanced engineering tools with diverse applications across industries such as healthcare, environmental monitoring, microbiology and food quality control. They play a crucial role in detecting pollutants, toxic elements and biohazards, as well as in clinical diagnostics and disease screening. The integration of nanotechnology has significantly enhanced biosensor performance by enabling rapid, sensitive and precise detection at the molecular level. Nanomaterials like nanoparticles, nanowires, carbon nanotubes (CNTs), nanorods and quantum dots (QDs) contribute to improved stability, conductivity and detection capabilities[18,19]. By leveraging nanoscale materials and

structures, these technologies achieve unprecedented levels of sensitivity, biocompatibility and functionality. Nanomaterials play a crucial role in the advancement of smart implants and biosensors. Some of the most commonly used nanomaterials include.

Graphene: Since its discovery in 2004, graphene has gained significant attention due to its exceptional properties, including a large surface area, superior mechanical strength and outstanding thermal and electrical conductivity. Various synthesis techniques, such as chemical, mechanical, thermal decomposition and chemical vapor deposition methods, enable large-scale graphene production[20]. Graphene-based nanomaterials mainly graphene, graphene oxide (GO) and reduced graphene oxide (rGO) are widely used in biosensors due to their unique properties. Graphene offers excellent conductivity, GO allows easy functionalization and rGO combines both conductivity and modifiability, making them ideal for diverse biosensing applications[21]. Graphene-based electrochemical biosensors are emerging as powerful tools for early oral cancer detection by analyzing salivary biomarkers. Graphene's high surface area, superior conductivity and mechanical strength contribute to highly sensitive and specific biosensors. Various electrochemical detection techniques, including voltammetry, impedance spectroscopy and photoelectrochemical methods, are explored. Challenges such as functionalization, stability and validation are highlighted. The future of graphene-based biosensors includes integration with AI, microfluidics and telemedicine, paving the way for personalized diagnostics and improved patient outcomes. Graphene exists in various forms, each tailored for specific applications. Monolayer graphene, a single-layer carbon sheet with exceptional electrical and thermal conductivity, is widely used in electronics, sensors and quantum computing. Bilayer and few-layer graphene (FLG) consist of two to ten layers, offering enhanced properties for use in batteries, composites and protective coatings. Graphene oxide (GO), with oxygen-containing functional groups, is highly dispersible in water and finds applications in water purification, drug delivery and flexible electronics. Reduced graphene oxide (rGO), a partially restored form of GO with improved conductivity, is commonly used in supercapacitors, coatings and biosensors. Graphene nanoplatelets (GNPs) are stacked layers of graphene known for their mechanical strength and thermal conductivity, making them ideal for reinforced composites, thermal management and lubricants. Doped graphene, modified with elements like nitrogen, boron, or sulfur, enhances catalytic and electrical properties, making it useful in sensors, energy storage and fuel cells. Finally, 3D graphene (foam/porous graphene), a high-urface-area structure, is used in lightweight materials, energy storage devices and environmental applications such as oil spill cleanup and water filtration[22]. Graphene-derived nanomaterials, such as graphene, graphene oxide, reduced graphene oxide, graphene quantum dots and graphene-based nanocomposites, have garnered considerable interest owing to their remarkable physical, chemical, biological and optoelectronic characteristics. These distinctive attributes render them very effective in numerous scientific uses, especially in the advancement of highly responsive biosensors. Multiple studies have evidenced their capacity to identify infections and biomolecules, facilitating quick disease diagnosis.

Biosensors are typically classified based on their biorecognition elements (antibody, aptamer, enzyme) or transducing mechanisms (electrochemical, optical, or mass-based). In biosensors utilizing graphene-derived materials (GDMs), electrochemical and optical methods are most preferred due to the superior electronic and optical properties of GDMs, as well as their versatility in manufacturing and material processing. Commonly used GDMs include flat graphene sheets, micrometric or nanoscale flakes of graphene oxide (GO) or reduced graphene oxide (rGO) and hybrid materials. These materials enhance the performance of biosensors by improving electro-optical recognition and facilitating specific analyte anchoring. The section details the design and fabrication strategies of electrochemical and optical GDM-based biosensors, including developments in miniaturized, remote and wearable devices and their application in detecting inflammatory disease biomarkers[23]. Graphene-based biosensors are used in advancing medical diagnostics and personal care through the development of devices with high sensitivity and low detection limits. Owing to their exceptional properties such as large specific surface area, outstanding electronic conductivity, rapid electron transport and remarkable flexibility graphene and its derivatives are increasingly being employed in biosensor fabrication. These materials enable the quantitative detection of cancer-related biomarkers, including DNA, microRNA (miRNA), small molecules and proteins. Various signal transduction methods are integrated into these biosensors, such as fluorescence, electrochemical responses, Surface Plasmon Resonance (SPR) and surface-enhanced Raman scattering (SERS), to ensure precise and reliable detection. In addition to summarizing the current advancements, the article discusses the key challenges faced in graphene biosensor development, such as stability, selectivity and reproducibility and explores potential solutions and future prospects for improving performance and expanding applications (Fig. 2).

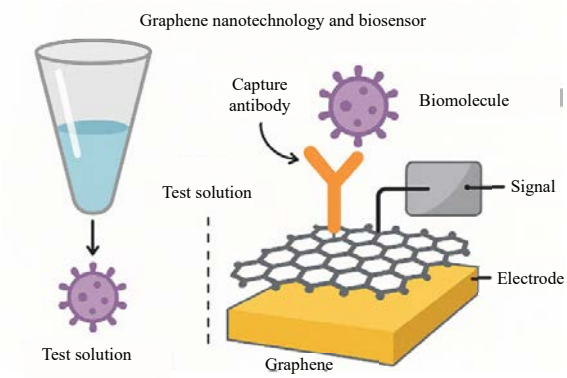


Fig. 2: Multi-Walled Carbon Nanotube (MWCNT) functionalization and bundle dispersion

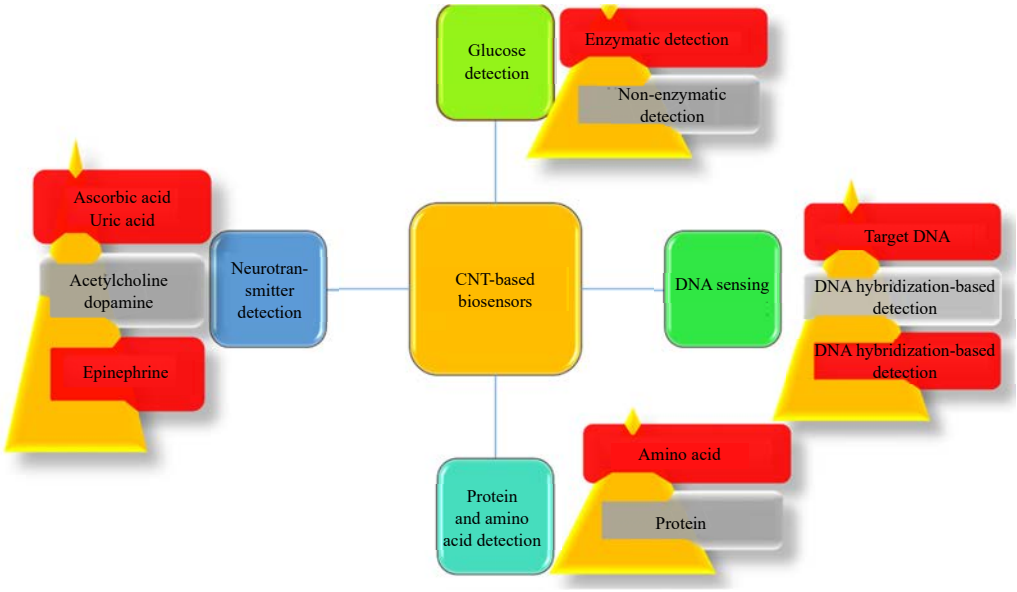


Fig. 3: Structure and electronic properties of Single-Walled (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs)

Carbon nanotubes (CNTs): Carbon nanotubes (CNTs) are highly versatile nanomaterials with exceptional mechanical, electrical and surface properties, making them ideal for smart implants and biosensors. In smart implants, CNTs enhance strength, durability, biocompatibility and serve as drug delivery vehicles. In biosensing, they enable highly sensitive detection of diverse biomolecules through various sensor types (electrochemical, optical, FET). Applications include glucose monitoring for diabetes, cancer biomarker detection, environmental pollutant sensing and integration into smart textiles for wearable health monitoring (Fig. 3). Functionalized Carbon Nanotubes (*f*-CNTs) are increasingly explored for applications in nanomedicine and bioengineering due to their unique properties. These properties, including exceptional physicochemical, mechanical, electrochemical and electrochemiluminescence characteristics, make *f*-CNTs ideal for a variety of biomedical and therapeutic strategies. Their potential applications include targeted drug delivery to specific tissues, enhancing drug bioavailability, reducing side effects and promoting tissue repair. Additionally, *f*-CNTs are employed in diagnostic, detection and monitoring devices. In bioengineering, they strengthen the structure of composite implants and contribute to the development of healing materials. This article focuses on recent advancements in *f*-CNT-based formulations for pharmaceutical nanoscience and bioengineering. Carbon nanotubes (CNTs) possess exceptional mechanical, thermal, electronic and biological properties due to their unique graphene-based cylindrical structure (Fig. 3). These characteristics have led to their exploration in various technological fields, particularly in biomedicine for applications such as biosensors, drug delivery systems and advanced implant materials. Despite promising

research outcomes, clinical in vivo use remains limited due to concerns about toxicity, biosafety and biodegradation. A major challenge is the lack of standardized toxicological assessments, which leads to inconsistent results. The development of CNT-based smart biomaterials for pathogen detection, targeted drug delivery and improved implant performance while emphasizing the need for clearer understanding of their toxicological profile for safe medical application[24].

Carbon nanotube (CNT)-based biosensors have emerged as a transformative tool in modern diagnostics due to their exceptional ability to detect biomolecules associated with various diseases in a rapid, accurate and cost-effective manner. Unlike traditional laboratory methods that are often time-consuming and complex, CNT-based biosensors offer real-time analysis and high sensitivity, making them ideal for early diagnosis, continuous health monitoring and point-of-care testing. The superior performance of these biosensors stems from the unique physicochemical and photoelectric properties of CNTs, including their large surface area, excellent electrical conductivity and strong mechanical and chemical stability. These properties enhance biomolecule immobilization and electron transfer, leading to faster and more reliable signal detection. CNTs have been successfully applied in the detection of critical biological targets such as glucose, DNA, proteins, amino acids and neurotransmitters. For instance, enzymatic and non-enzymatic glucose sensors utilizing CNTs are widely used in diabetes management, while DNA sensors benefit from CNTs' ability to facilitate hybridization and signal amplification for gene or pathogen detection. Similarly, protein and amino acid sensors leveraging CNTs are crucial in identifying disease biomarkers and neurotransmitter sensors are valuable in diagnosing neurological disorders like Parkinson's and Alzheimer's diseases. Continuous improvements in sensor design, such as the integration of CNTs with nanoparticles, polymers, or graphene and the development o f flexible, miniaturized and wearable devices, further enhance detection performance. The incorporation of AI and machine learning into biosensor platforms also promises smarter data analysis and predictive diagnostics. Looking ahead, CNT-based biosensors hold great potential in personalized medicine, telehealth and decentralized diagnostics, although challenges related to toxicity, biocompatibility and large-scale production must still be addressed. Overall, these biosensors represent a powerful convergence of nanotechnology and biomedical science aimed at improving global healthcare outcomes[25].

Quantum dots: Quantum dots (QDs) are semiconductor nanocrystals only a few nanometers in size, exhibiting unique optical and electronic properties due to quantum mechanical effects. When exposed to ultraviolet light, QDs absorb energy, exciting electrons from the valence band to the conduction band[26]. As these electrons return to their original state, they emit light a process called photoluminescence with the color determined by the energy gap between bands. Quantum dots can confine electrons in all three dimensions, leading to discrete energy levels and atom-like behavior, making them highly tunable for various applications in nanotechnology and materials science[27]. Quantum dots (QDs) are gaining significant attention as powerful tools in the development of smart implants and advanced biosensors due to their exceptional optical properties and compatibility with biological systems. These nanoscale semiconductor crystals can be engineered to emit light of specific wavelengths when exposed to light energy, making them highly useful as fluorescent labels. What sets QDs apart from traditional fluorescent dyes is their superior brightness, photostability and tunability allowing precise control over their emission based on size and composition. In biosensing applications, QDs can be functionalized with biomolecules such as antibodies, peptides, or nucleic acids, enabling them to selectively bind to target analytes like disease biomarkers, pathogens, or toxins. This makes them excellent candidates for early disease detection and real-time monitoring. Furthermore, their small size and surface chemistry also allow QDs to be integrated into implantable medical devices, where they can simultaneously serve diagnostic and therapeutic roles, such as tracking physiological changes or delivering drugs to specific tissues (Fig. 4). Their capacity for multi-analyte detection, identifying several targets simultaneously further enhances their potential for use in next-generation biosensors and personalized medicine. As research advances, QDs are expected to play a critical role in bridging nanotechnology with smart biomedical devices for improved patient care and health monitoring[28].

Point-of-Care (PoC) denotes clinical diagnostic tests conducted in proximity to the patient, as opposed to being executed in a central laboratory. It refers to obtaining prompt results at or near the location of patient care. PoC testing assists physicians in making rapid treatment decisions, which enhanced early diagnosis and is particularly crucial in distant, resource-constrained, or emergency environments. Common examples include blood glucose meters, pregnancy tests and rapid COVID-19 tests[29]. Quantum dots (QDs) enhance Point-of-Care (PoC) diagnostics by offering high sensitivity, brightness and multiplexing capabilities for rapid detection of disease

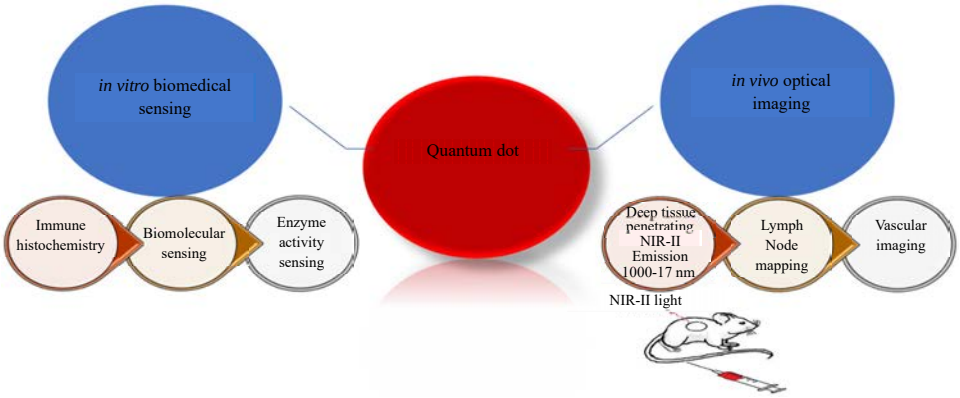


Fig. 4: Synthesis pathways, surface modification and biomedical applications of quantum dots

Table 1: Comparison of different quantum dots

QD Type	Composition	References
Cadmium selenide (CdSe) QDs	CdSe core, often with ZnS/ZnSe shell	Ganti *et al.*[31]
Indium phosphide (InP) QDs	InP/ZnSe/ZnS	Won *et al.*[32]
Graphene quantum dots (GQDs)	Graphene sheets, sp^2 carbon, <10 nm, O/H edge groups	Kumar *et al.*[33]
Perovskite quantum dots ($CsPbX_3$)	All-inorganic $CsPbX_3$ (X = Cl, Br, I)	Tien *et al.*[34]
Copper indium sulfide ($CuInS_2$) QDs	$CuInS_2$/ZnS core/shell (review)	Varghese and Oluwafemi[35]
Lead sulfide (PbS) QDs	PbS core, colloidal, tunable bandgap 0.5–1.7 eV (NIR-active)	Wu and Ning[36]
Carbon quantum dots (CQDs)	Surface-passivated carbon nanoparticles, tunable PL	Baker and Baker[37]
Silicon QDs (SiQDs)	Hydrogen-terminated silicon nanocrystals	Chinnathambi *et al.*[38]
$CsPbX_3$ (Perovskite QDs)	$CsPbBr_3$, $CsPbI_3$, etc. (foundational synthesis)	Protesescu *et al.*[39]
Ag_2S (Silver sulfide)	Ag_2S core, NIR-II emitting	Zhang *et al.*[40]

biomarkers. Their tunable fluorescence allows simultaneous detection of multiple targets in compact, portable devices. QDs are integrated into lateral flow assays, microfluidic chips and smartphone-based readers for real-time results. This makes them ideal for quick, accurate testing in remote, clinical, or emergency settings. Quantum dots (QDs) are semiconductor nanocrystals that exhibit unique optical and electronic properties, distinctly different from their bulk counterparts due to quantum confinement effects. At the nanoscale, electrons in QDs are confined in all three spatial dimensions, leading to discrete energy levels, which result in highly tunable and size-dependent photoluminescence. This means that by simply changing the size of the QDs, their emission color can be precisely controlled from blue to near-infrared making them ideal for multiplexed imaging and sensing. In addition, QDs possess a narrow and symmetric emission peak, a broad excitation spectrum and high brightness with exceptional photostability, which makes them superior to traditional organic dyes and fluorescent proteins. These optical properties are harnessed in a variety of biomedical applications, including molecular imaging, biosensing and advanced diagnostic systems. Particularly in molecular imaging, QDs allow for real-time visualization of cellular and molecular processes with high resolution. In biosensing, QDs can be functionalized with biomolecules like antibodies, aptamers, or peptides to detect specific targets such as DNA, proteins, or pathogens, often with high sensitivity and specificity. The article places special emphasis on the integration of QDs into point-of-care (PoC) testing platforms, which are designed to deliver rapid diagnostic results at or near the site of patient care. QDs enhance PoC systems by enabling sensitive detection of biomarkers even at low concentrations and facilitating multiplexed assays within portable, user-friendly devices. These advancements are particularly impactful in low-resource settings and emergency situations where immediate clinical decisions are necessary. With the development of QD-based lateral flow assays, microfluidic devices and smartphone-integrated detection systems, quantum dots are paving the way for next-generation PoC diagnostics that are fast, accurate and accessible[30]. A comparative study has been given in Table 1.

Nanostructured coatings: Nanostructured coatings are thin films composed of nanoscale materials that are engineered to enhance the surface properties of substrates for a wide range of applications. Due to their high surface-area-to-volume ratio and tunable chemical, mechanical and optical characteristics, these coatings offer improved performance compared to conventional coatings[41]. They can provide exceptional antibacterial, anti-corrosive, self-cleaning, anti-fouling and

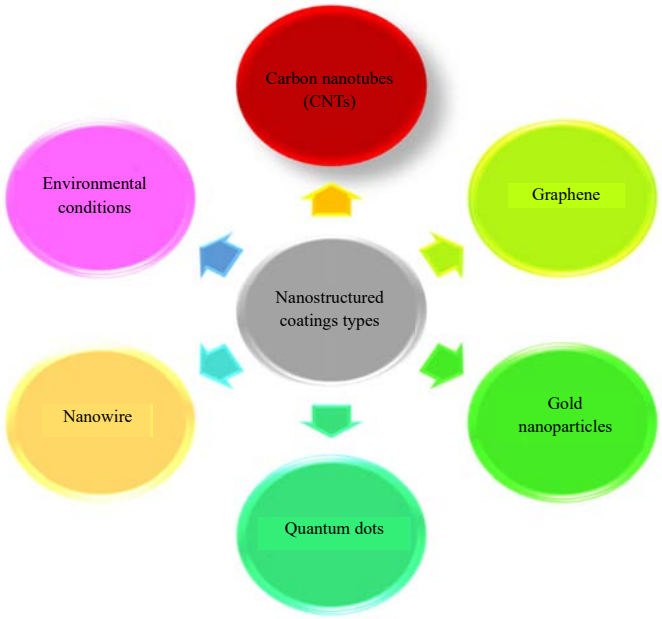


Fig. 5: Synthesis mechanisms and structural morphologies of graphene derivatives

wear-resistant properties, making them highly valuable in biomedical devices, electronics, aerospace and environmental technologies. In the biomedical field, nanostructured coatings are applied to implants, surgical instruments and diagnostic tools to enhance biocompatibility, reduce infection risk and promote cell adhesion and tissue integration (Fig. 5). These coatings may include materials like metal nanoparticles (silver, titanium), carbon-based nanostructures (graphene, CNTs), or bioactive ceramics, often deposited using techniques such as sol-gel, sputtering, or electrospinning. Their ability to tailor surface interactions at the nanoscale makes them indispensable for developing next-generation functional materials[42].

Nanomaterials have paved the way for the development of nanostructured coatings, featuring components at the nanometre scale, which provide exceptional surface protection (Fig. 5). These coatings are vital across industries like electronics, medicine, food packaging and shipping. Nanostructured coatings, such as metallic coatings, ceramic nanocoatings and nanocomposite coatings (which combine metals or polymers with nanomaterials), demonstrate enhanced performance in resisting corrosion and wear (tribological behavior). Key factors such as grain size, composition, synthesis techniques, environmental conditions and the addition of modifiers significantly impact the effectiveness of these coatings (Fig. 5). Additionally, biomimetic strategies designs inspired by nature are being employed to create next-generation nanocoatings with superior functionalities.

A nanoparticle-based biosensor is a device that can detect biological molecules or chemical substances with high sensitivity, selectivity, resolution, reproducibility and fast response time. These qualities ensure that the sensor gives accurate and consistent readings under various conditions. Traditional biosensors often faced challenges in efficiently transmitting signals between the bioreceptor (the part that detects the target molecule, like an antibody or enzyme) and the transducer (which converts that detection into a readable signal). This is where nanoparticles (NPs) offer a breakthrough. Due to their nanoscale dimensions and high surface-area-to-volume ratio, NPs can bridge the gap between the bioreceptor and the transducer more effectively than bulk materials. This results in enhanced electron transfer, stronger signal amplification and overall better performance of the biosensor. The use of electrochemical techniques (where the sensor measures electrical changes resulting from biochemical interactions) in combination with NPs has led to the creation of biosensors with remarkably improved sensitivity and detection limits. These nanosensors can detect very low concentrations of target substances, making them ideal for early disease diagnosis, environmental monitoring and food safety applications[43].

Mechanisms of nanotechnology-enhanced biosensors: Nanotechnology-enhanced biosensors utilize nanoscale materials to significantly improve the detection capabilities, sensitivity and overall performance of conventional biosensors. These enhancements arise from several

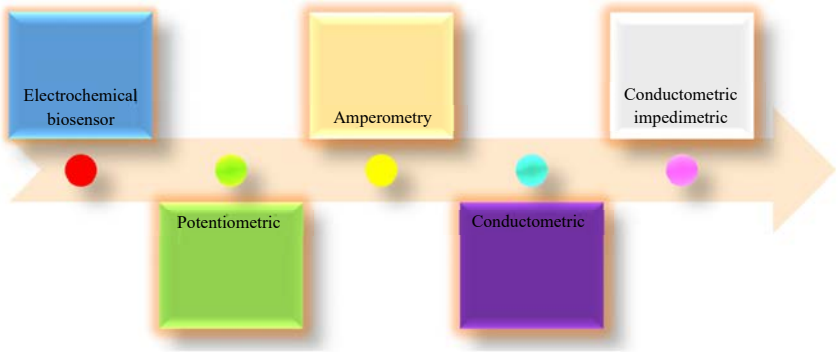


Fig. 6: Electrochemical biosensors parts based on the uses such as Potentiometric, Amperometry, Conductometric

mechanisms. Signal amplification is a key mechanism; nanomaterials like gold nanoparticles, carbon nanotubes and quantum dots facilitate stronger and more detectable signals (electrochemical, optical, thermal, or magnetic) due to their excellent conductivity, fluorescence and catalytic properties. Increased surface area provided by nanostructures (nanowires, nanotubes, dendrimers) allows for higher loading of biorecognition elements such as enzymes, antibodies, or DNA probes, improving the biosensor's sensitivity and response time. Efficient electron transfer between the bioreceptor and the transducer is enabled by conductive nanomaterials, which accelerates the sensor's reaction to target analytes. Target-specific binding is enhanced by the functionalization of nanomaterials with molecular recognition agents, improving selectivity and minimizing interference. Real-time detection and multiplexing become possible with nanomaterials like quantum dots, which emit distinct fluorescence signals based on their size, enabling simultaneous detection of multiple analytes. These mechanisms collectively make nanotechnology-enabled biosensors powerful tools in medical diagnostics, environmental monitoring, food safety and biosecurity. Nanotechnology improves electrochemical biosensors by utilizing nanoscale materials to significantly boost their sensitivity, specificity and overall performance in analyte detection. These nanomaterials facilitate stronger interactions between biological recognition elements (BREs) and the electrochemical transducer, thereby enhancing signal transduction and amplification. Nanomaterials, with their unique electrochemical properties and high surface area, enhance electrochemical sensor performance and enable diverse biomedical applications[44].

Electrochemical sensing: An electrochemical biosensor detects and measures the concentration of a specific analyte by converting a biological interaction into an electrical signal. This is achieved by immobilizing a biological recognition element (like an enzyme, antibody, or DNA probe) onto an electrode surface. When the target analyte binds or reacts with this element, it leads to a chemical change, typically oxidation or reduction, that alters electrical properties such as current (amperometry), voltage (potentiometry), conductance, or impedance. These changes are then measured and correlated to the analyte's concentration[45]. electrochemical biosensors and lab-on-a-chip devices are the essential tools for delivering rapid and on-site diagnostic. These tools are used in various fields such as medical diagnostics, food safety, environmental monitoring, process control, wastewater treatment and life sciences research (Fig. 6). A well-known example is the glucose sensor used by people with diabetes. The detection process begins when the analyte of interest undergoes a chemical reaction at the electrode or sensing element, typically involving oxidation or reduction (Fig. 6). This electrochemical interaction results in the generation of an electrical signal, which may manifest as a change in current, potential, or impedance. The magnitude of this electrical response is directly proportional to the concentration of the analyte, thereby enabling accurate quantitative analysis. Electrochemical sensors are rapidly evolving due to high demand and technological advancements. They offer a cost-effective and versatile approach for detecting various analytes across sectors like agriculture, food, oil, environment and biomedicine (Fig. 6). Their popularity lies in diverse signal outputs (voltage, current, power, impedance) and high sensitivity due to Faradaic and non-Faradaic current differences[46].

Electrochemical biosensors can be classified into several categories, including potentiometric, amperometric, conductometric and voltammetric sensors, depending on the detection principle. Additionally, they can be categorized based on the type of biological recognition element used, such as immunosensors, DNA sensors, or microbial sensors.

One of their major advantages is their ability to function effectively in complex or turbid media, where traditional optical methods may fail. These biosensors provide highly

sensitive and specific readouts by translating biological interactions into measurable electrical signals. In recent years, the application of DNA and RNA-based electrochemistry in biosensing has gained significant traction, particularly in the field of infectious disease diagnostics[47]. By detecting specific nucleic acid sequences, these biosensors have been successfully employed in identifying various viral infections, including hepatitis E, Coronavirus (such as SARS-CoV-2), HIV, influenza and Zika virus, as well as bacterial and parasitic diseases like malaria. Their high specificity and rapid response time make them valuable tools for early diagnosis, disease surveillance and point-of-care testing, especially in resource-limited settings.

Molecularly imprinted polymers (MIPs) and surface imprinted polymers (SIPs) have emerged as promising artificial receptors due to their high selectivity and robustness[45]. Electrochemical sensing nanotechnology integrates electrochemistry with nanotechnology to develop highly sensitive and specific sensors. By utilizing the unique properties of nanomaterials, this approach significantly improves sensor performance, enabling applications in medical diagnostics, environmental monitoring and food safety. Nanomaterials such as nanowires, nanotubes and graphene are widely used in applications like biomarker and pathogen detection. Ongoing research in this field is expected to revolutionize healthcare by enabling rapid, accurate and accessible diagnostics[48-50].

Food security is increasingly challenged by mass food production, global imports and evolving consumption habits, making food safety control essential. Rapid and sensitive screening methods, including biosensors, have emerged to detect pathogens and freshness biomarkers. Electrochemical biosensors, in particular, offers high specificity and accuracy even in complex food matrices, making them valuable for food contaminant detection. The development and application of these biosensors across major food categories meat, fish, dairy and beverages addressing key food safety concerns, enable efficient monitoring of contaminants, spoilage indicators and pathogens, ultimately ensuring safer and fresher food products for consumers.

OPPORTUNITIES, LIMITATIONS AND FUTURE CHALLENGES

Opportunities: It offers enormous opportunities in healthcare and biosensing devices, offering high precision, real-time monitoring and improved patient outcomes. Coatings on nanostructures such as TiO_2 nanotubes, graphene and hydroxyapatite nanoparticles improve osseointegration, reduce rejection and minimizes the inflammation. Nanostructured surfaces enhance cell adhesion, proliferation and differentiation, ultimately leading to better implant fixation. These play a very crucial role in healthcare amenities, mainly, dental, orthopedic and cardiovascular implants. For instance, the titanium implants coated with hydroxyapatite nanoparticles display bone bonding. Nanocomposites can adapt to physiological changes which ultimately helps in increasing the life longevity. Nanoelectronics allow smaller and smarter implants. Gold nanoparticles, carbon nanotubes normally increase the sensitivity for biomarker detection at very small scale (femto/pico). Nanoscale transducers allow continuous glucose monitoring, cancer marker detection, or neurotransmitter sensing. Portable nano biosensors can provide rapid diagnostics for personalized medicine. These are linked to wireless platforms enable smart healthcare systems for real-time health monitoring. Long-term effects of nanomaterials (carbon nanotubes, quantum dots, metal oxides) in the body remain uncertain. While producing reproducible, cost-effective nanostructures at scale is challenging. Sensor drift, biofouling and degradation in complex biological environments reduce accuracy over time. Smart nano systems require sustainable, biocompatible power with micro-batteries, biofuel cells, wireless energy transfer. Lack of clear approval pathways for nanotech-based implants/sensors complicates commercialization. Continuous health monitoring raises cybersecurity and privacy concerns. The next stage requires addressing fundamental scientific, technical and regulatory challenges. Establishing global standards for nanomaterial toxicity, safety and reproducibility. Understanding immune response, degradation and clearance of nanomaterials. Development of energy-harvesting or biodegradable nano-power sources for fully autonomous smart implants. Moving from lab-scale fabrication to mass production without losing precision. Combining nanotech with AI, machine learning, flexible electronics and bioinformatics for predictive healthcare. Addressing privacy, accessibility and equitable distribution of advanced nanomedical technologies. Nanotechnology offers enormous opportunities for making smart implant more biocompatible and biosensors more sensitive and real time, but it faces a serious limitation in biocompatibility, stability and regulatory approval. The future challenges inhibit in developing secure, safe, scalable and ethically approved solutions which can be integrated into the mainstream healthcare.

Limitations: Due to its tiny size, nanoparticles can pass through biological barriers and gather in organs such as the brain, liver and lungs. Uncertainty surrounds the long-term consequences of this bioaccumulation, which may include

DNA damage or inflammation. The immune system of the body can perceive nanomaterials as foreign, triggering unwanted immune responses. This can lead to inflammation and compromise the function of implants. It behaves differently from their bulk counterparts, making their toxicity difficult to predict through traditional testing methods. A standardized approach for safety evaluation is still in development.

Challenges: One of the main challenges in case of smart implants are immunological reactions, where the sensitive components are contaminated with proteins and other substances over the period of time, encapsulated in fibrous tissue due to foreign body response, leading to changes in the output signals or failure of the sensors. Technical problems with pressure sensors might also arise, such as abrupt changes or slow baseline pressure drift during intracranial pressure monitoring. In case of chemical sensing, the major challenges posed includes integration of chemical sensors with various types of implants.

CONCLUSION

Nanotechnology has significantly advanced the development of smart implants and biosensors, enabling precise interaction between biological systems and engineered materials. The use of nanomaterials such as graphene, carbon nanotubes, quantum dots and nanostructured titanium dioxide has improved device sensitivity, miniaturization and biocompatibility. These innovations have enhanced real-time detection of biomolecules, facilitated effective tissue integration and reduced immune responses, thereby strengthening the link between diagnosis and therapy. Nanostructured coatings, energy-harvesting systems and nanoengineered drug reservoirs represent crucial steps toward intelligent and autonomous biomedical devices. Furthermore, nanotechnology-based drug delivery systems allow site-specific and controlled release of therapeutic agents, minimizing toxicity and maximizing therapeutic efficacy. Self-powered systems utilizing piezoelectric or triboelectric nanogenerators have opened new avenues for long-term implantable devices that require minimal maintenance. Despite these promising achievements, key challenges such as the reproducibility of nanomaterial synthesis, long-term in vivo stability, biosafety and regulatory validation still hinder large-scale clinical translation. Addressing these issues through standardized fabrication techniques, long-term toxicity assessments and interdisciplinary collaboration is essential to ensure safe and reliable clinical applications. In conclusion, nanotechnology continues to transform biomedical science by enhancing the performance, adaptability and reliability of implants and biosensors. With ongoing innovation and rigorous evaluation, these nanoscale technologies hold strong potential to improve disease monitoring, therapeutic delivery and overall patient care in the coming decades.

SIGNIFICANCE STATEMENT

This review highlights the transformative role of nanotechnology in advancing smart implants and biosensors for precision healthcare. It demonstrates how nanomaterials and nanoscale engineering can improve biosensing sensitivity, tissue integration, energy harvesting and controlled drug delivery. By critically discussing current applications, technological advances, translational challenges and future opportunities, this review provides a comprehensive perspective on the development of intelligent, self-powered, minimally invasive and personalized biomedical systems. The insights presented may support future research aimed at overcoming biosafety, scalability, stability and regulatory barriers and accelerating the clinical translation of nanotechnology-enabled healthcare technologies.

ACKNOWLEDGMENT

Authors would like to thank Dr. Dinesh Kulhary for his meaningful suggestions. Additionally, one of the authors, Dr. Arun, expresses sincere gratitude to Dr. Anil Yadav for their insightful discussions, regarding biosensors.

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