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REVIEW ON NANOMATERIAL BASED BIOSENSOR FOR CANCER DETECTION

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1. ABSTRACT

A specific protein or gene-based biomarker is increased or altered in bodily fluids or tissues at the start of cancer. The survival rate can be significantly increased or effective treatment using various modalities can be facilitated by early detection of these markers. Even while advanced imaging methods like Computed Tomography, Positron Emission Tomography, and Magnetic Resonance Imaging have enhanced performance due to nanotechnology, they are not appropriate for the early detection or quantification of cancer biomarkers. For early cancer diagnosis, other methods based on cell shape and microscopy (biopsies) are also insufficient. The only chance for early cancer diagnosis in the near future is through the use of nanotechnology-reformed immunoassays and sensors to identify cancer biomarkers. The design, production, sensitivity, and multiplexing of these immunoassays/sensors in biomarker detection have all been amazingly improved by the attractive qualities of nanoparticles. In this section, we have examined the latest developments in immunogens methods that were created by taking advantage of the special qualities of gold nanoparticles. We have also talked about potential future developments in single-molecule biosensing, paper-based analytical tools, and gold nanoparticle-coupled microfluidic sensors. Devices for the detection and measurement of physical or chemical properties at the nanoscale, with applications in health care, environmental monitoring, industrial processes and food safety. Early detection and diagnosis of cancer is essential for successful treatment and better patient outcomes. Types of nanosensors used in the detection of cancer includes optical, magnetic and electrochemical elements. Quantum dots, carbon nanotubes and gold nanoparticles offer unique advantages in

cancer diagnosis and treatment, enabling accurate imaging, targeted drug delivery and better treatment strategies. Gold nanoparticles have several mechanisms of action in the treatment of cancer, including photothermal therapy, cancer cell targeting, biomarker discovery, imaging techniques and nanosensors. They can generate heat, improve the effectiveness of radiotherapy and target cancer cells for targeted drug delivery. They can also be linked to biomarkers, which allow early diagnosis and monitoring of the disease. Recent advances in Nanosensors have improved sensitivity and specificity, allowing non-invasive and efficient cancer screening. Functionalized nanoparticles and signal amplification techniques can improve the sensitivity and detection limits of nanosensors, reducing further concentrations of cancer cells.[1]

2. KEYWORDS: Biosensor, Nanomaterials, Cancer Diagnosis, Nanotechnology, Biomarker Detection, Nanoparticle's, Cancer Therapy.

3. INTRODUCTION

Definition of Nanosensors

In conclusion, nanomaterial-based biosensors hold immense promise for early and accurate cancer detection, enabling timely medical intervention and better patient outcomes. Ongoing research continues to explore new nanomaterials, surface modification techniques, and signal transduction mechanisms to further improve the performance and reliability of these innovative diagnostic tools.

Nanosensors are miniature devices capable of detecting and measuring various physical phenomena. or chemical properties at the nanoscale. These sensors use nanotechnology to improve their sensitivity and precision, which allow them it detects even the smallest changes in its environment. Nanosensors have a wide range of applications, from healthcare and environmental monitoring to industrial and food processes security.

Cancer is one of the leading causes of death worldwide, characterized by uncontrolled cell growth and the potential to invade or spread to other parts of the body. Early detection of cancer is crucial for successful treatment and improved patient survival rates. Conventional diagnostic techniques, such as biopsy, imaging, and immunoassays, though effective, are often time-consuming, costly, and require highly specialized equipment and expertise. Hence, there is a growing need for rapid, sensitive, and cost-effective diagnostic tools capable of detecting cancer at an early stage.

In recent years, biosensors have emerged as promising analytical devices for disease diagnosis, offering high sensitivity, specificity, and real-time detection capabilities. A biosensor is an analytical device that combines a biological recognition element (such as enzymes, antibodies, nucleic acids, or cells) with a transducer that converts the biological response into a measurable electrical, optical, or mechanical signal. The performance of a biosensor greatly depends on the efficiency of its transducer material and surface properties, where nanomaterials play a vital role.

Nanomaterials, due to their unique physical, chemical, and biological properties, have revolutionized the field of biosensing. Their large surface area-to-volume ratio, excellent electrical conductivity, optical tunability, and biocompatibility make them ideal for improving the sensitivity and detection limits of biosensors. Various nanomaterials such as gold nanoparticles (AuNPs), carbon nanotubes (CNTs), graphene, quantum dots (QDs), and metal oxide nanoparticles have been integrated into biosensing platforms to enhance signal amplification and biomolecule immobilization.

In the context of cancer detection, nanomaterial-based biosensors can identify cancer biomarkers— such as proteins, nucleic acids, and metabolites—at very low concentrations in biological fluids (blood, urine, or saliva). These biosensors enable early diagnosis, personalized medicine, and realtime monitoring of disease progression. For instance, gold nanoparticle-based electrochemical biosensors have been used to detect prostate-specific antigen (PSA) for prostate cancer, while graphene oxide-based optical biosensors have shown great potential in detecting breast cancer biomarkers like HER2.

The Integration of nanotechnology with biosensor technology represents a significant advancement in cancer diagnostics. It bridges the gap between laboratory research and clinical application by offering portable, reliable, and cost-effective diagnostic tools.

However, challenges such as biocompatibility, stability, reproducibility, and large-scale manufacturing still need to be addressed before these devices can be widely adopted in clinical settings.

- Importance Of Early Detection And Diagnosis Of Cancer

Early detection and diagnosis of cancer is essential for successful treatment and improvement of living conditions for patients. results . Nanosensors play an important role in this field that allows the detection of cancer early stage biomarkers, which allow rapid analysis personalized interventions and treatment plans.

Moreover, nanosensors offer the potential for this non-invasive real-time cancer monitoring progress, provides valuable information on effectiveness of therapies and treatment directions decisions.

- Purpose Of The Review

The purpose of this review is to explore the current situation advances in nanosensor technology for the first detection and diagnosis of cancer. Examining the latest research and developments, we aim to highlight the potential benefits and limitations of nanosensors to improve patient outcomes and guidance. personalized treatment strategies.

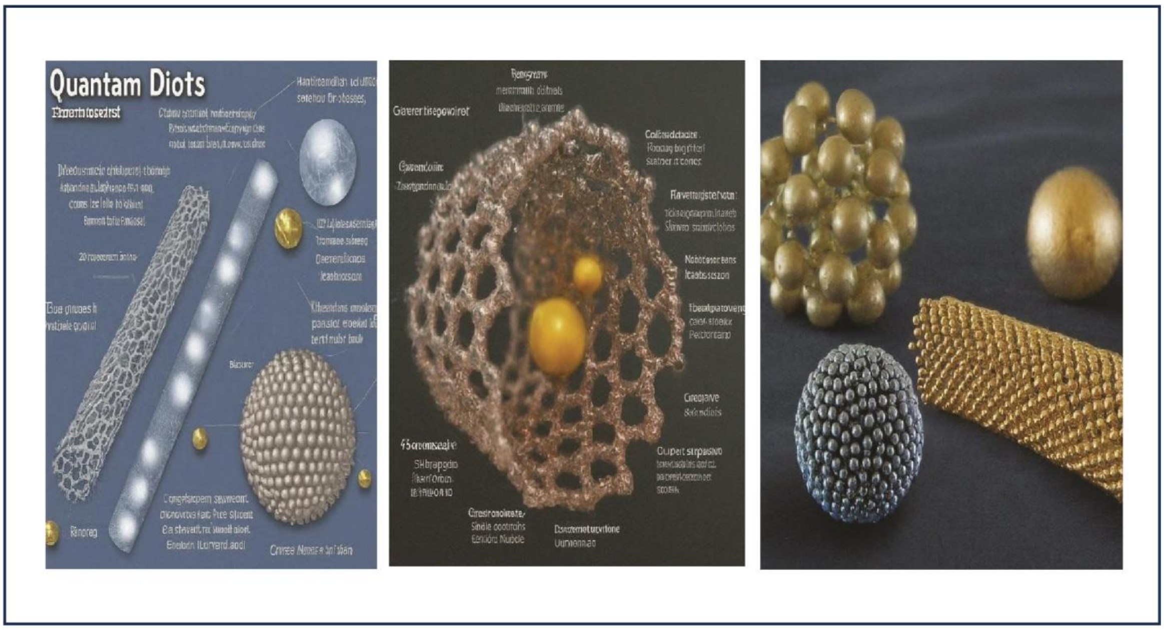

Fig No 1. Nano Powerhouses

Nano powerhouses: quantum dots: these tiny semiconductor particles can be engineered to emit light of different colors when stimulated, allowing them to target and identify specific cancer cells. They can also be used to deliver drugs directly to cancer cells. Carbon nanotubes: these cylindrical structures have unique properties that make them useful for cancer research and treatment. They can be used to deliver drugs, image tumors, and even destroy cancer cells. Gold nanoparticles: these nanoparticles have unique optical properties that make them suitable for imaging and therapy. They can be used as contrast agents in imaging techniques like CT scans, and they can also be coated with drugs for targeted therapy.[1]

4. Principles of Biosensing for Cancer Detection

1. Basic Concept of a Biosensor

A biosensor is an analytical tool that uses a physicochemical transducer and a biological recognition element to identify particular biological analytes.[3-4]

2. Principle of Operation

The principle of biosensing for cancer detection involves:

i. Specific Binding: A biomolecule (bioreceptor) binds to a cancer biomarker (e.g., HER2, PSA, CEA) in a particular way.

ii. Signal Transduction: The transducer transforms the change in mass, charge, light, heat, etc. brought about by this binding into an electrical or optical signal. Signal processing measures the concentration of the biomarker by amplifying, filtering, and analyzing.[5]

3. Types of Transduction Principles

Biosensors for cancer detection operate based on various transduction mechanisms.[6]

4. Biological Recognition Elements

The specificity of a biosensor depends on the bioreceptor used:

Table No. 01[7]

Bioreceptor Type	**Example Application**
Antibodies	Detection of specific cancer antigens (e.g., CEA, CA-125)
DNA Probes	Identification of oncogenes or mutations (e.g., BRCA1/2)
Aptamers	High-affinity detection of cancer proteins
Enzymes	Catalytic detection linked with tumor metabolism
Whole Cells	Detection of tumor cell activity

5. Key Performance Parameters

A good biosensor for cancer detection should haves

- **High Sensitivity** – detect very low biomarker concentrations.
- **High Specificity** – distinguish cancer biomarkers from normal ones.
- **Fast Response Time** – provide rapid results.
- **Stability** – maintain accuracy over repeated use.
- **Miniaturization** – suitable for point-of-care testing (POCT).[8]

6. Examples of Cancer Biomarkers Detected Using Biosensors

Table No: 02.

Cancer Type	Biomarker	Biosensor Type
Breast Cancer	HER2, CA 15-3	Electrochemical, SPR
Prostate Cancer	PSA	Electrochemical
Liver Cancer	AFP (Alpha-fetoprotein)	Optical
Ovarian Cancer	CA-125	Electrochemical
Lung Cancer	CEA, microRNA	Optical, Nanobiosensor.

7. Emerging Trends

- **Nanomaterial-based biosensors** (e.g., gold nanoparticles, graphene, quantum dots) for enhanced sensitivity.
- **Microfluidic lab-on-a-chip devices** for rapid and low-cost cancer diagnostics.
- **Wearable and point-of-care biosensors** for continuous cancer monitoring.
- **Artificial intelligence (AI)** integrated biosensors for data interpretation and predictive analysis.[9]

5. Role of Nanomaterials In Biosensors

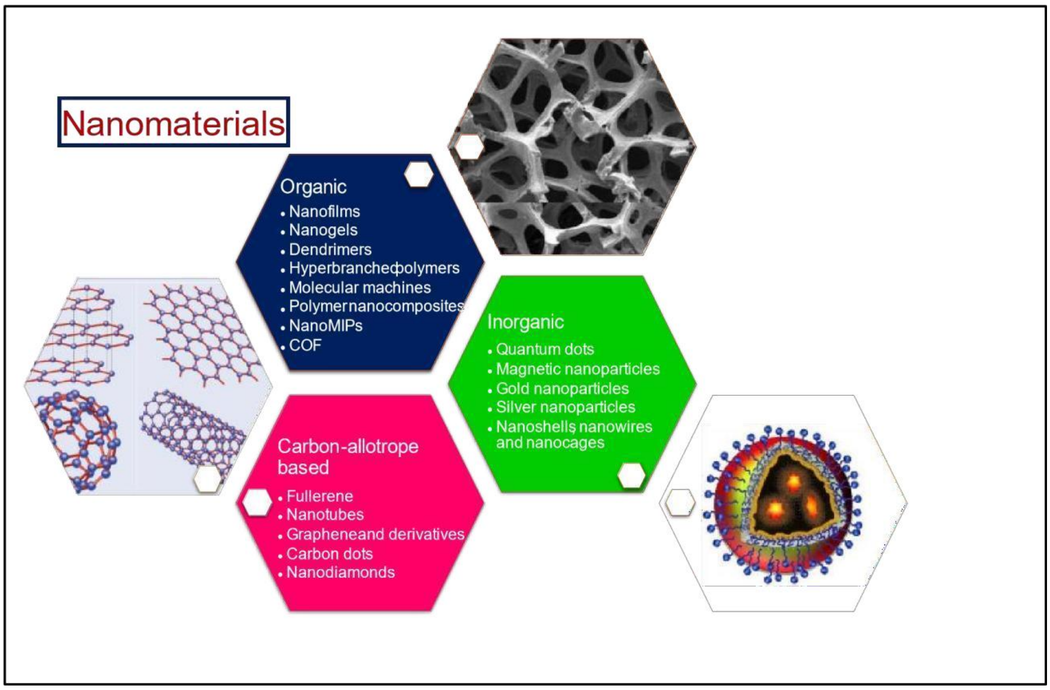

Fig No. 02: Various kinds of nanomaterials discussed in this review.

There are two primary methods for creating nanomaterials: top-down and bottom-up. The topdown method involves designing and controlling a macroscale machine to create a smaller, identical clone of itself. The process is repeated until nanoscale dimensions are reached, with this smaller machine creating an even smaller replica. The bottom-up technique uses biotechnology, scanning probes, or supramolecular chemistry to assemble individual atoms or molecules to create bigger structures . The bottom-up strategy is more widely used, even though both of the previously stated methods are essential to the production of nanomaterial-based biosensors.

Faster, more affordable, more sensitive, and more accurate medical diagnostic tests and equipment have been made possible by advances in nanotechnology. Chemistry, molecular engineering, material science, and biotechnology are among the fields that are brought together by biosensors that use nanomaterials.

Early illness screening is made possible by the use of nanotechnology to identify disease biomarkers at incredibly low abundance. This has the potential to improve medical methods needed for routine prognosis to track patient diagnosis and follow-up operations. Additionally, point- ofcare (POC) diagnostics in nations without sophisticated medical facilities depends on the integration of nanotechnology and biosensing.[2] A schematic of inorganic nanoparticles with relation to several types of biomarkers is shown in Figure 2, along with a linear flow that illustrates each step of biosensing, from analyte detection to transduction, and finally a measurable signal that is processed and shown. We give a thorough overview of the use of nanoparticles in healthcare sensing in the sections that follow.

6. Types Of Nanosensor Used In Cancer Treatment

There are many types of nanosensors used in cancer detection, including optical nanosensors, magnetic nanosensors, and electrochemical nanosensors. Each type of nanosensor has its own their advantages and limitations, but they all have them the potential to revolutionize the diagnosis of cancer and treatment. Optical nanosensors, for example, can detect changes in the emission or absorption of light when they come into contact with cancer cells or biomarkers. Magnetic nanosensors can use magnetic fields to detect and quantify specific cancer-related molecules. Electrochemical nanosensors can measure changes in electrical signals when interacting with substances linked to cancer.[5-7] These different types of nanosensors provide researchers and clinicians with a variety of options to develop personalized and targeted cancer therapy.

- Optical Nanosensor

These sensors use light to detect changes in the cancer cells or biomarkers. For example, they can discover changes in the amount of light absorbed or emitted from cancer cells. Quantum dots are a type of optics nanosensor.

- Magnetic Nanosensor

These sensors use magnetic fields to detect and quantify specific cancer molecules. They they can be very sensitive and specific, but they need it specialized equipment.

- Electrochemical Nanosensor

These sensors measure changes in electrical signals when they interact with cancer-related substances. They are relatively simple and cheap, but may not be as sensitive as other types of nanosensors.

- Quantum Dots

They offer quantum dots, another type of nanosensor Unique advantages in the diagnosis and treatment of cancer. These tiny semiconductor particles emit Light of different colors when stimulated, which allows a highly sensitive and specific detection of cancer biomarkers.

Furthermore, quantum dots can be engineered to specifically target cancer cells, enabling accurate imaging and targeted drug delivery for more effective treatment strategies.

- Carbon Nanotubes

Carbon nanotubes, another type of nanosensor, have promising in cancer research and treatment. These cylindrical structures have remarkable properties mechanical strength and electrical conductivity, making them ideal for applications such as drug delivery and imagine. Also, carbon nanotubes can be functionalized with specific to selective molecules bind to cancer cells, facilitating targeted therapy and minimize damage to healthy tissues.

- Gold Nanoparticles

Gold nanoparticles, on the other hand, have unique properties. optical properties that make them suitable for imaging and therapy. Its small size allows it easily penetrates tissues and accumulates in tumors; making them excellent contrast agents for images techniques such as computed tomography (CT) the analysis. Also, gold nanoparticles can be coated with drugs or therapeutic molecules, which allow the direct delivery of drugs directly to cancer cells while minimize side effects on healthy tissues.[7] Figure 2 illustrates the different mechanisms of action used by gold nanoparticles in cancer therapy, including: Photothermal therapy: Heat generation after exposure to light for the target cell destruction Radiosensitization: improving the effectiveness of radiation therapy by producing cancer cells more vulnerable. Targeted drug delivery: Specific binding to cancer cells for a specific drug delivery Biomarker discovery:

single element binding cancer markers for early diagnosis and treatment surveillance These versatile nanoparticles contain tremendous potential to improve cancer treatment the results.[10]

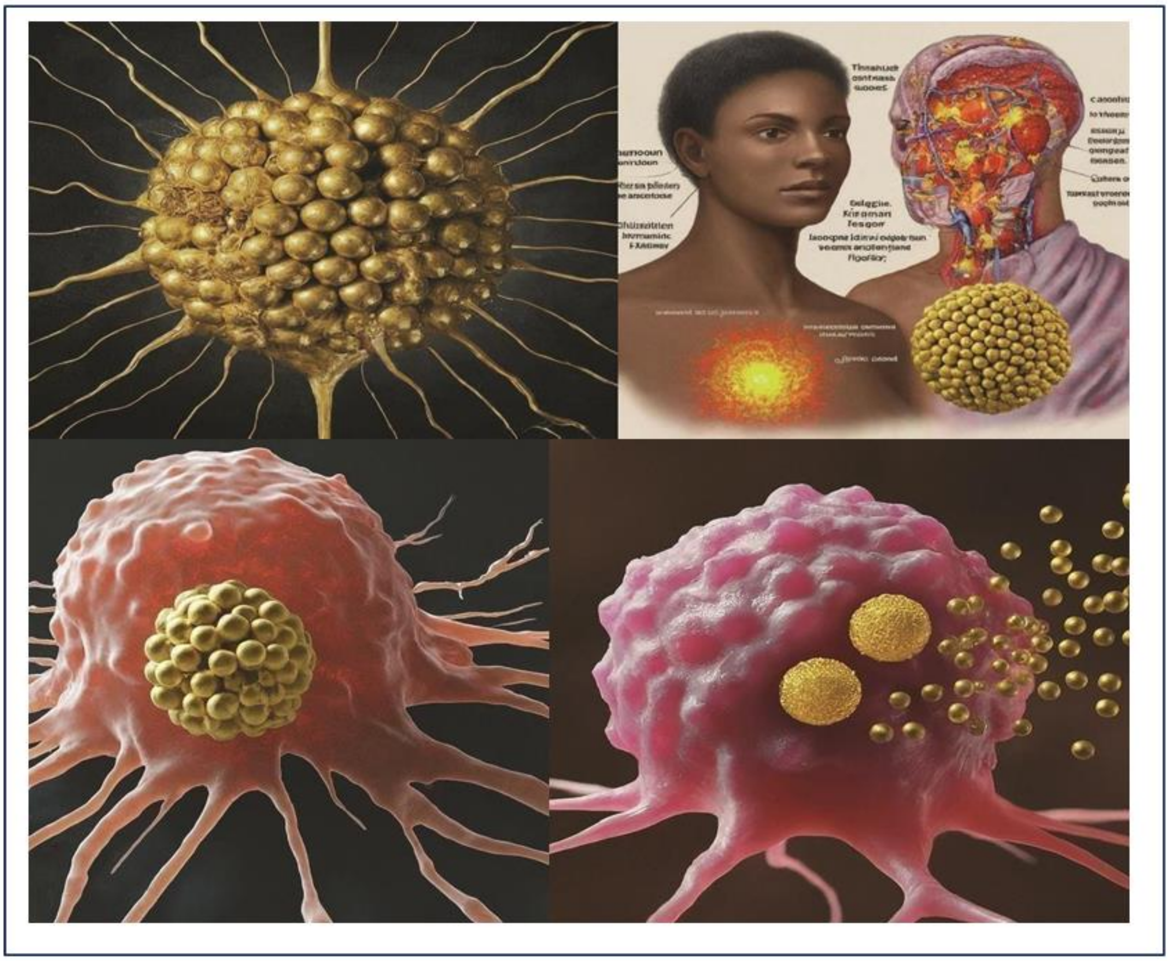

Fig. No. 03: Unveiling the power of gold.

7. Recent Advances in nanomaterial-based biosensors for cancer detection:

Recent advances in nanomaterial-based biosensors have revolutionized cancer detection, enabling highly sensitive, noninvasive, and multiple assays of cancer biomarkers, essential for early diagnosis and improved patient outcomes.[11]

○ Key nanomaterial in Biosensors

Nanoparticles (NPs), nanowires (NWs), nanowheels (NRs), carbon nanotubes (CNTs), quantum dots (QDs) and graphene derivatives are widely used. Carbon-based nanomaterials, including graphene, carbon nitride, and carbon quantum dots, are notable for their excellent surface chemistry, large surface area, and high sensitivity.[12] o Major technological innovation

1. Multiplexed biosensors

Recent developments allow the simultaneous detection of multiple cancer biomarkers, providing comprehensive diagnostic data important for prognosis and monitoring.[13]

2. Liquid biopsies

Advanced biosensors can analyze circulating tumor cells, cell-free DNA, or exosomes from blood or other fluids, enabling non-invasive real-time cancer monitoring.[14]

3. Electrochemical platforms

Nanocomposites, such as MXent, gold nanoprism, and hybrid graphene quantum dot gold systems, contain advanced electrochemical biosensors, which improve sensitivity and specificity for various types of cancer (eg, breast, thyroid, cervical, and gastric cancer).[15]

4. Optical biosensors

Nanostructured illumination and surface plasmon resonance techniques provide powerful tools for the rapid and reliable detection of DNA, proteins and transcriptomic biomarkers.[16]

- AI & future Direction

Integrating biosensors with artificial intelligence enables automated pattern recognition, data analysis and improved diagnostic accuracy for complex biomarker signatures. Future biosensor architectures will continue to focus on portability, accessibility, and performance for point-ofcare or wearable cancer diagnosis.

Summary Table: Recent Advances (2024-2025).[17]

Table No. 03

Nanomaterial Type	**Application**	**Advantages**	**Example Biomarkers**
Carbon nanomaterial	Electrochemical, optical	High sensitivity, easy functionalization	HER2, CD44, Vimentin
Quantum dots	Luminescence detection	Colour tunability, multiplex analysis	HPV 16 DNA
Nanocomposites (hybrid)	Immunoassay, ECL detection	Signal amplification, stability	Breast cancer proteins
Graphene/Au hybrids	Electrochemistry, SERS	Large surface area, selectivity	Gastric cancer proteins

8. Challenges and Limitations

1. Toxicity and Biocompatibility Issues

Numerous nanomaterials, such as metallic nanoparticles, carbon nanotubes, and quantum dots, have the potential to induce inflammation, oxidative stress, or cellular toxicity. Safe elimination from the body and long-term biocompatibility are still unknown. The lack of toxicological data makes regulatory approval challenging.[18]

2. The Synthesis of Nanomaterials Is Not Standardised

Size, shape, surface charge, and functionalisation are examples of properties that need to be closely regulated. Sensitivity and repeatability are impacted by variable sensor performance caused by batch variation.[19]

3. Problems with Stability and Degradation

In physiological settings, nanomaterials may clump, oxidise, or deteriorate, which would lower their sensing accuracy.

When exposed to blood, serum proteins, and salts, stability deteriorates and can result in misleading results.[20]

4. Complex Biological Matrix Interference

Proteins, enzymes, and ions found in real clinical samples (blood, plasma, and saliva) can obstruct the surfaces of nanoparticles. Because of the decreased selectivity, false positives or negatives are produced.[21]

5. Clinical Translation Difficulties

Many sensors perform incredibly well in vitro, but biological noise or irregular biomarker levels cause them to fail in actual clinical settings. Costly validation and regulatory compliance are necessary when transitioning from lab prototypes to clinical-grade devices.

6. High Fabrication Costs

It can be expensive to carefully synthesise high-quality nanomaterials and integrate them into electrical or microfluidic systems.

It is still difficult to scale up for mass production.[22]

7. Connectivity to Point-of-Care Equipment

It is difficult to transform a nanomaterial sensor into a portable, easy-to-use diagnostic tool. requires solid power supplies, steady signal processing, and miniaturisation.

8. Limited Capability for Multiplexing

A single nanomaterial platform for the simultaneous detection of several cancer indicators is still in its infancy. Due to tumour heterogeneity, multi-biomarker profiling is ideal for cancer detection.[23]

9. Ethical and Regulatory Obstacles

Medical equipment based on nanotechnology are subject to stringent regulatory inspection, which lengthens the clearance process. Patient safety and the long-term effects of nanoparticles on the environment raise ethical questions

10. Issues with Reproducibility and Reliability

Sensor responsiveness can be significantly changed by little variations in the surface chemistry of nanomaterials. Different laboratories may produce different results, which makes clinical adoption challenging.[24]

9. Future Prospects

Biosensor technology has become one of the most studied fields due to its simplicity, speed, low cost, high sensitivity and high selectivity, all of which contribute to the next generation of medical advances. Therefore, the development of biosensors for medical and laboratory diagnostics is interesting and important. The discovery of biomarkers associated with different types of cancer is a major priority in the development of biosensors. In recent years advances

In biosensors related to breast cancer (BC) have become a major research focus for scientists. Recent advances in bioengineering and exploitation of labelled fluorescent nanomaterials significantly increased the sensitivity limits of the biosensors. Additionally, the incorporation of aptamers, nucleotides, affibodies, peptide arrays, and molecularly imprinted polymers provides. innovative tools for developing improved biosensors compared to conventional methods.

Other advancements in bio sensing technology include wearable sensors and artificial intelligence, which are aimed at precision medicine to enhance medical treatment These innovations make it easier to improve patient data collection and analysis by integrating biosensors with classical algorithms and pattern recognition techniques. The use of nanomaterials and nanotechnologies has significantly increased the sensitivity of biosensors for in vitro diagnostics, while paper-based biosensors offer a cost-effective alternative that maintains high sensitivity and allows sophisticated design implementation. According to the results obtained in this study, there appears to be a pathway to developing the ideal biosensor for gene detection. This biosensor can not only provide fast and accurate results, but also operate at the nanoscale. Such skills are essential for early detection and surveillance of breast cancer.

10. CONCLUSION

Biosensors based on nanomaterials offer a potent and revolutionary method for precise and early cancer diagnosis. Even at extremely low concentrations, their special qualities—such as high surface area, remarkable electrical and optical sensitivity, and tunable functionalization—allow for the quick and extremely sensitive identification of cancer biomarkers. These biosensors greatly increase diagnostic accuracy, shorten detection times, and create opportunities for pointof-care testing by combining nanomaterials like graphene, carbon nanotubes, gold nanoparticles, and quantum dots with sophisticated sensing platforms. Even though there are still issues with largescale production, biocompatibility, and clinical validation, research is still being done to increase their practical potential. All things considered, nanomaterial-based biosensors present a promising path towards earlier cancer patient detection, individualised treatment, and better survival rates.

Nanomaterial-based biosensors represent a transformative advancement in the early detection and management of cancer. Their unique nanoscale properties—such as high surface-to-volume ratios, tunable optical and electrical characteristics, and exceptional biocompatibility—enable ultra- sensitive, rapid, and specific detection of cancer biomarkers that traditional diagnostic tools often fail to identify at early stages. By integrating metallic nanoparticles, carbon-based nanomaterials, quantum dots, and advanced hybrid nanostructures with modern transduction mechanisms, these biosensors provide powerful platforms for point-of-care, minimally invasive, and real-time cancer diagnosis.

Despite challenges related to toxicity, stability, large-scale synthesis, and regulatory approval, continuous progress in nanofabrication, surface engineering, and machine learning–assisted biosensing is rapidly overcoming these limitations. Emerging technologies such as microfluidic lab- on-chip systems, wearable sensors, and AI-driven diagnostic algorithms are further enhancing the clinical potential of nanobiosensors.

Overall, nanomaterial-based biosensors hold immense promise for revolutionizing cancer diagnostics by offering faster, more accurate, and cost-effective detection strategies. With ongoing interdisciplinary research, these technologies are expected to bridge the gap between laboratory innovation and clinical application, ultimately improving patient outcomes through earlier and more precise cancer detection.

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